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Mixing and tuning in the superheterodyne receiver

MitchElectronics
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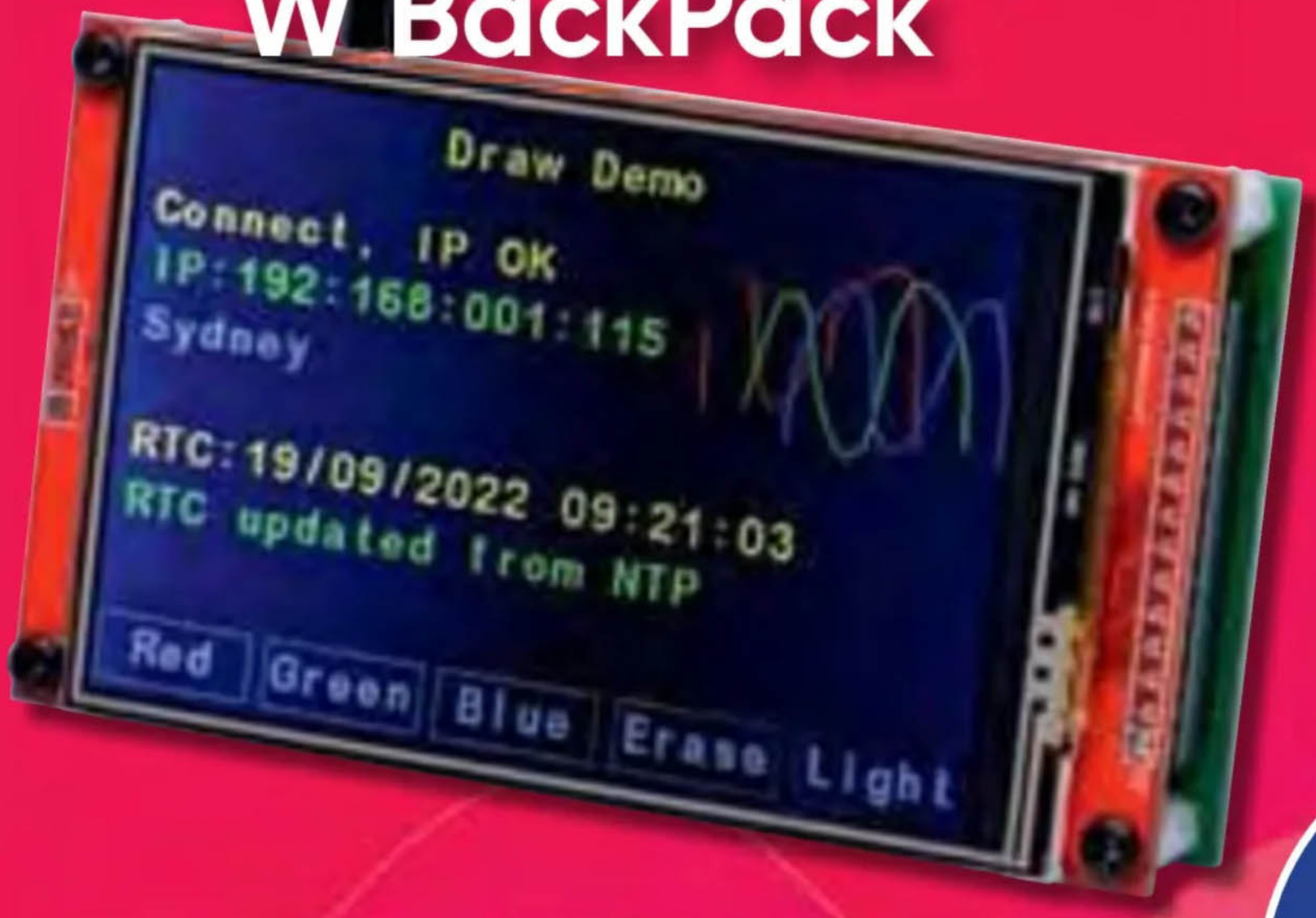
Audio Out
Discrete op amp update

Raspberry Pi Pico W BackPack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Cool Beans – Arduino: switching with transistors

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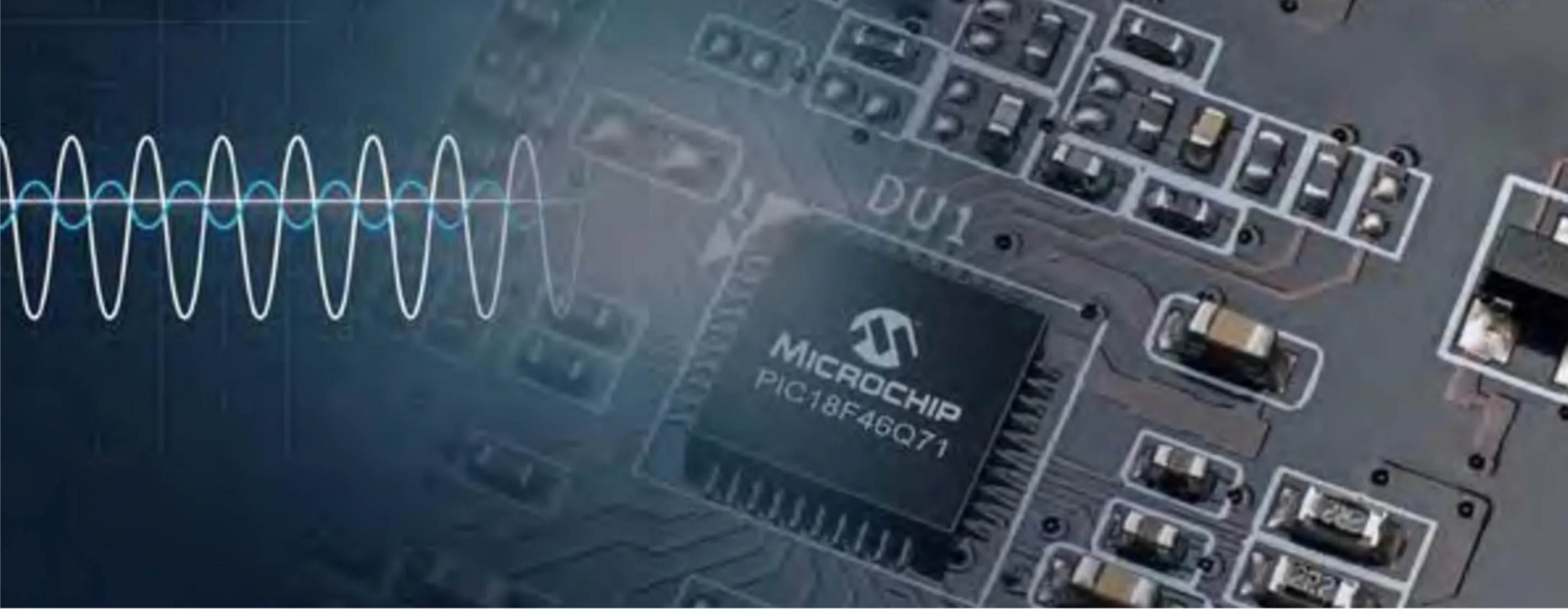

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Volume 53. No. 1
January 2024
ISSN 2632 573X

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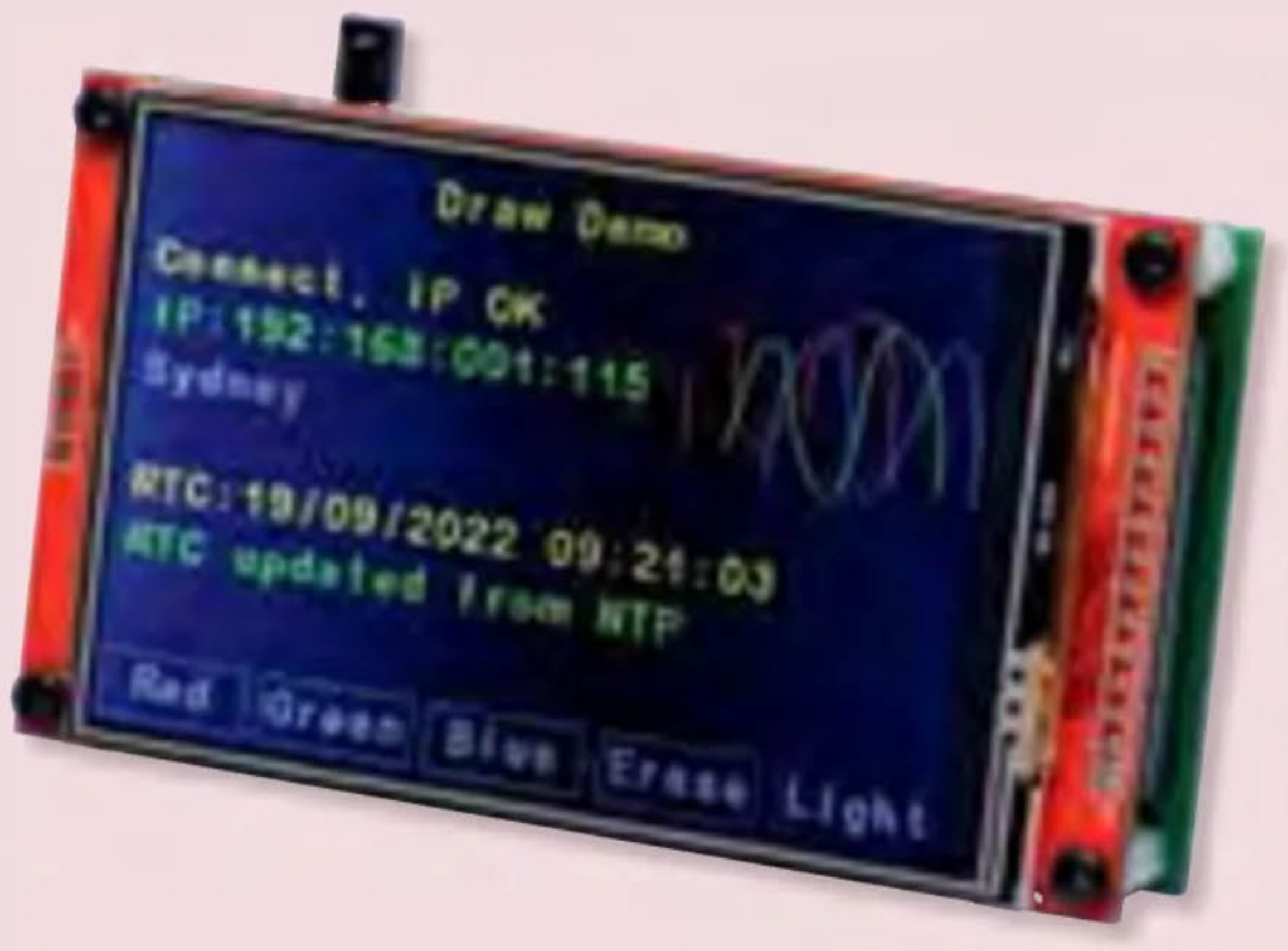

Projects and Circuits

Q Meter by Charles Kosina 18
We've published numerous LC meters that can measure inductance and capacitance, but you might need to know the quality factor (Q) of an inductor, not just its inductance. This Q Meter uses a straightforward circuit to measure Q up to values of about 200.

Raspberry Pi Pico W BackPack by Tim Blythman 26
Our Raspberry Pi Pico BackPack from March 2023 has a powerful dual-core 32-bit processor, 480 × 320 pixel colour touchscreen, onboard real-time clock, SD card socket, stereo audio output and infrared receiver. Now, for about £5 more, it has Wi-Fi too!

Active Subwoofer – Part 1 by Phil Prosser 32
This subwoofer is designed to be a no-compromise approach to a 'sub', making it a perfect match for a high-quality home theatre system, or as part of a high-fidelity stereo system.

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Made in the UK.

Written in Britain, Australia, the US and Ireland.

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The February 2024 issue of *Practical Electronics* will be published on Thursday, 4 January 2024 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

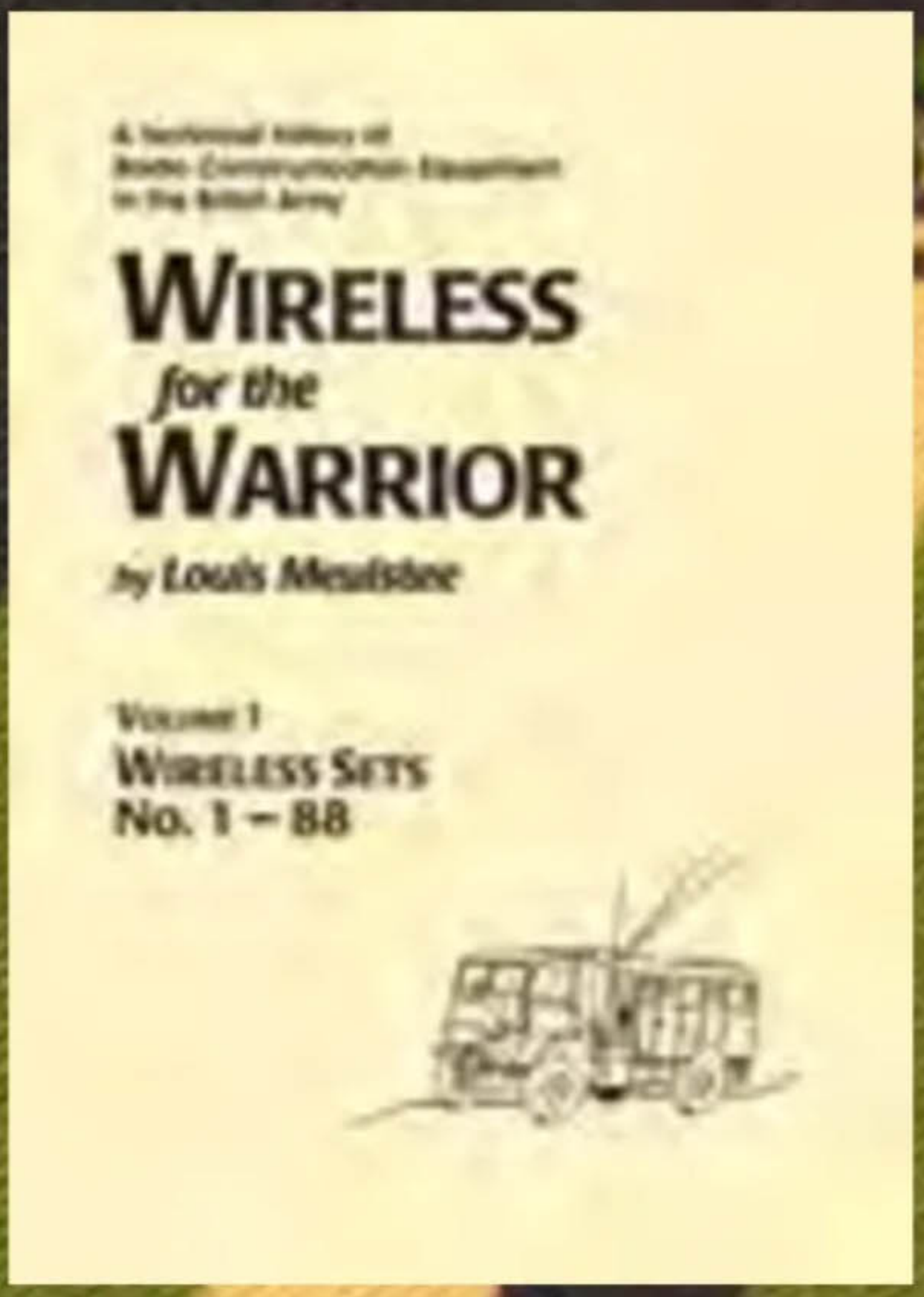
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

***Volume 1* and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.**

***Volume 3* covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.**

***Volume 4* covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.**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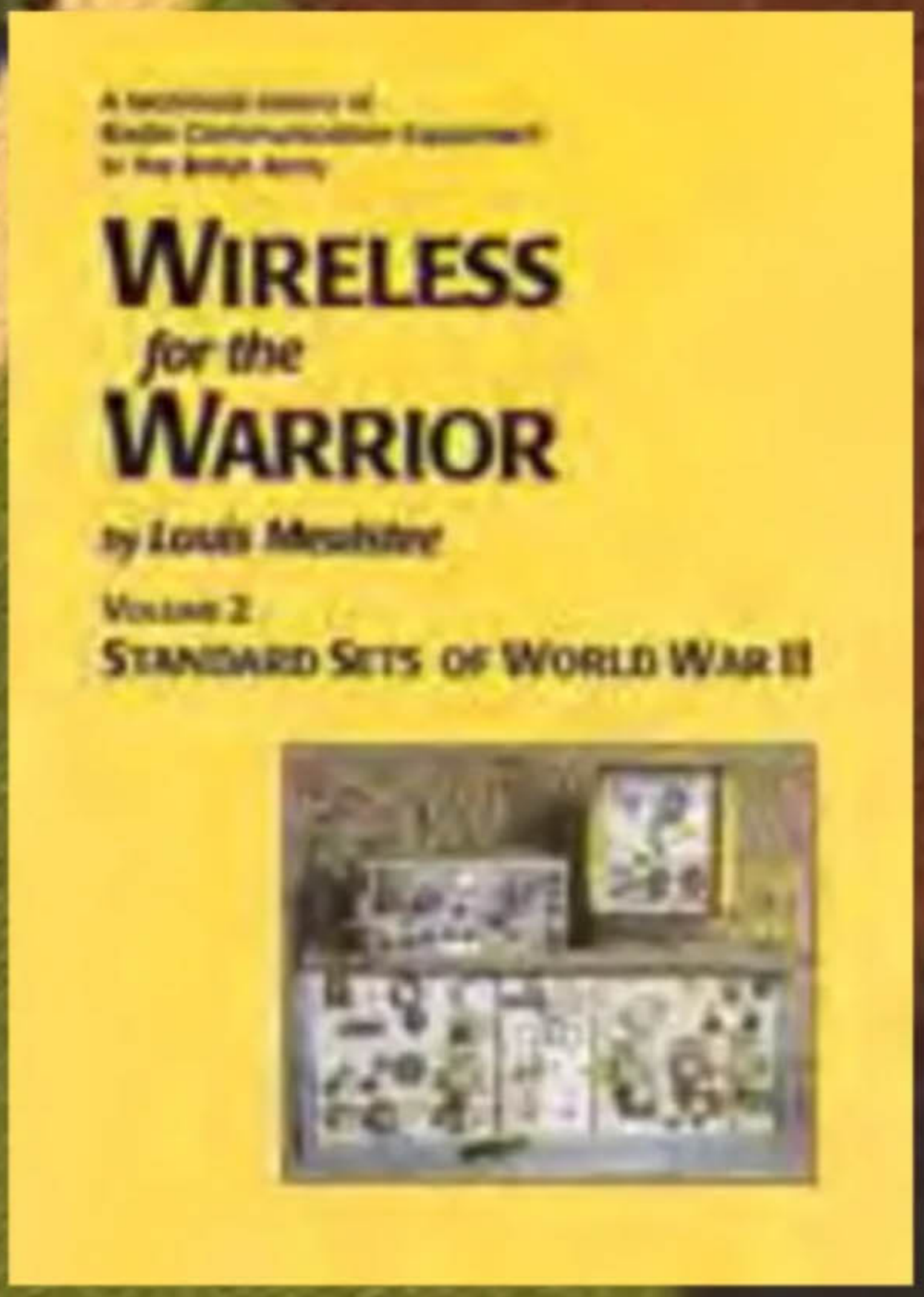
Volume 1
Wireless Sets No. 1 – 88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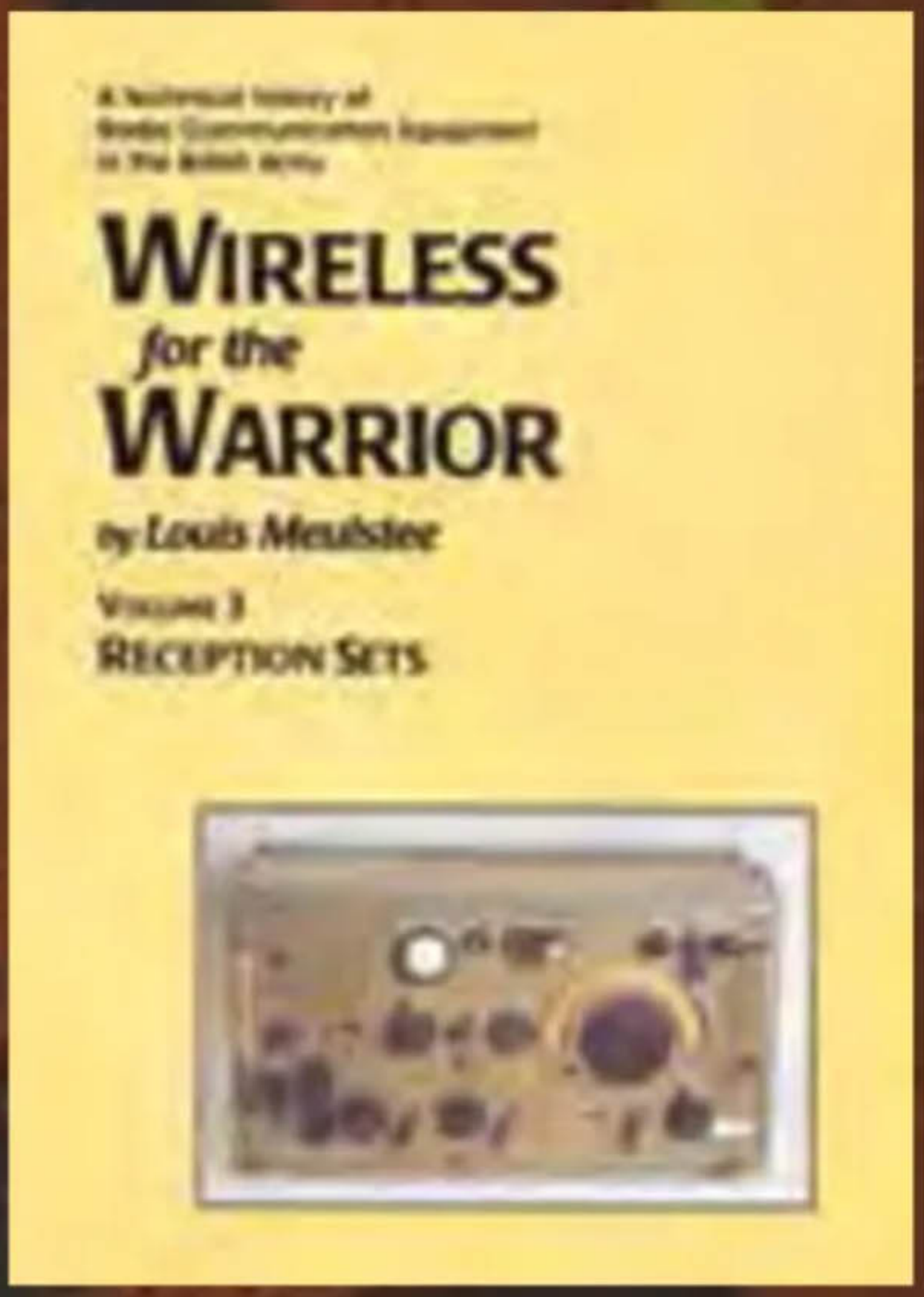
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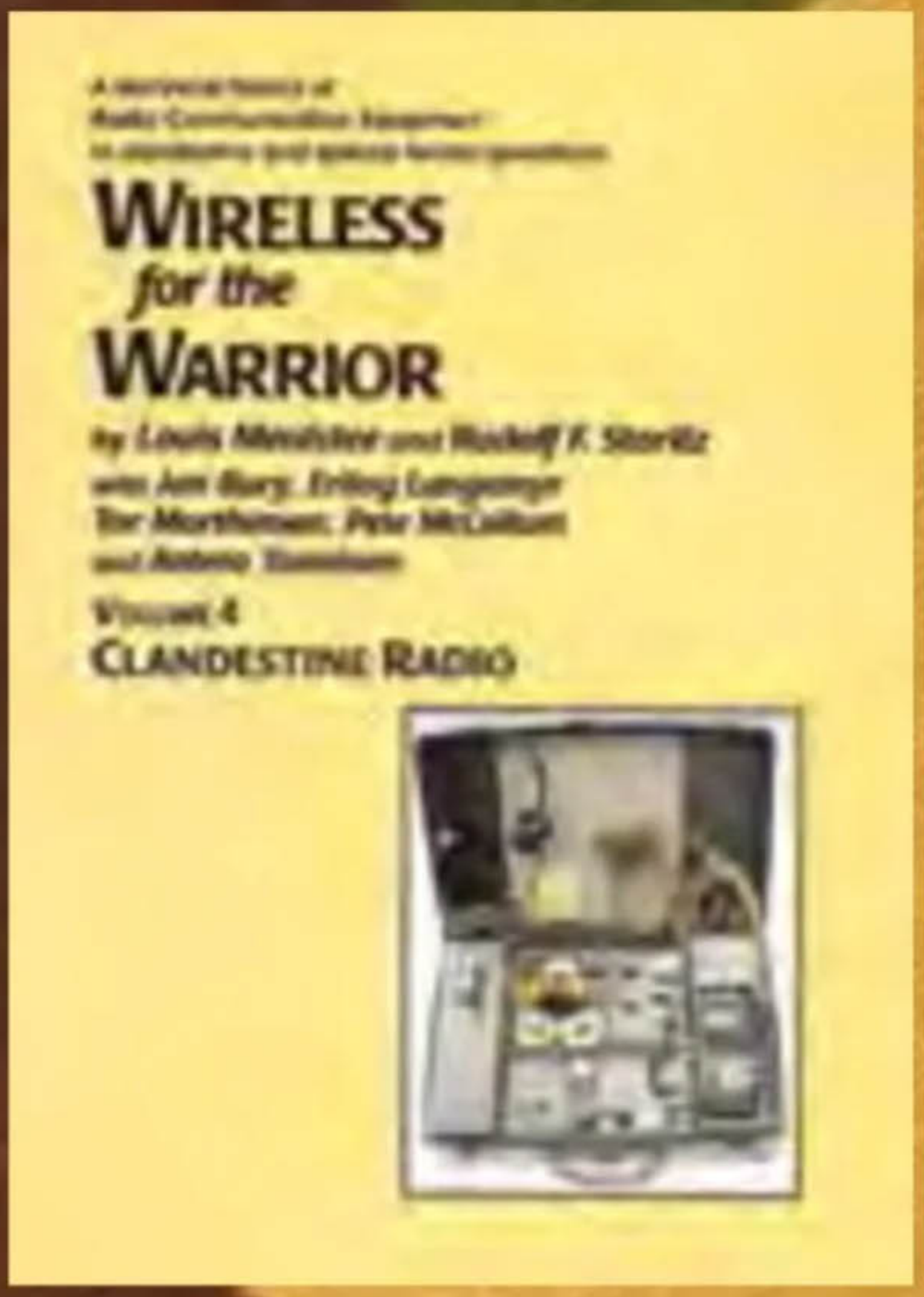
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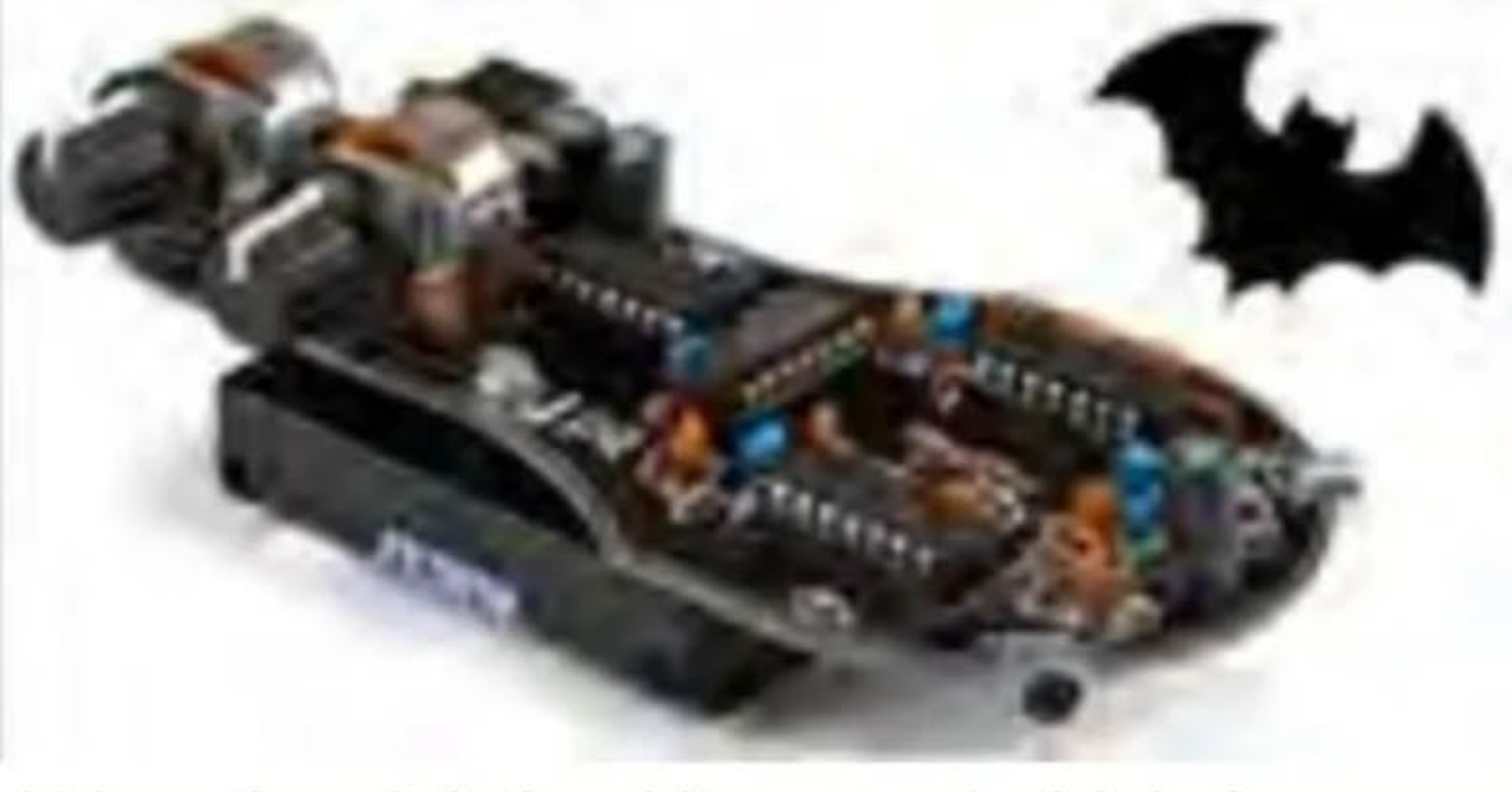

Educational & fun kit converts high frequency sounds (20 - 90kHz) normally imperceptible to humans like bat signals into audible noise. Can also help detect failures in machines, engines, etc. Stereo feature adds the possibility to pinpoint the source. Frequency range 20-90kHz. 3.5mm jack output. 129x60x40mm. Requires 3x AA batteries and stereo headphones (not included).
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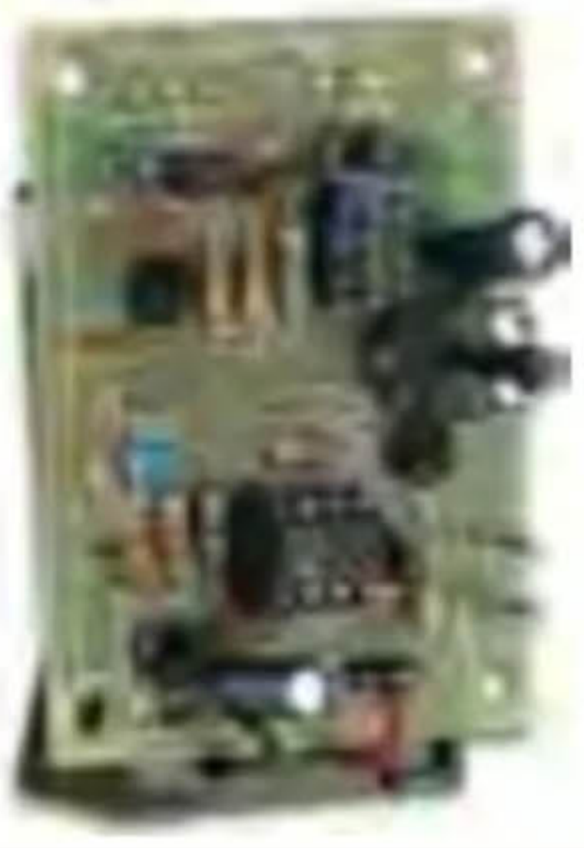

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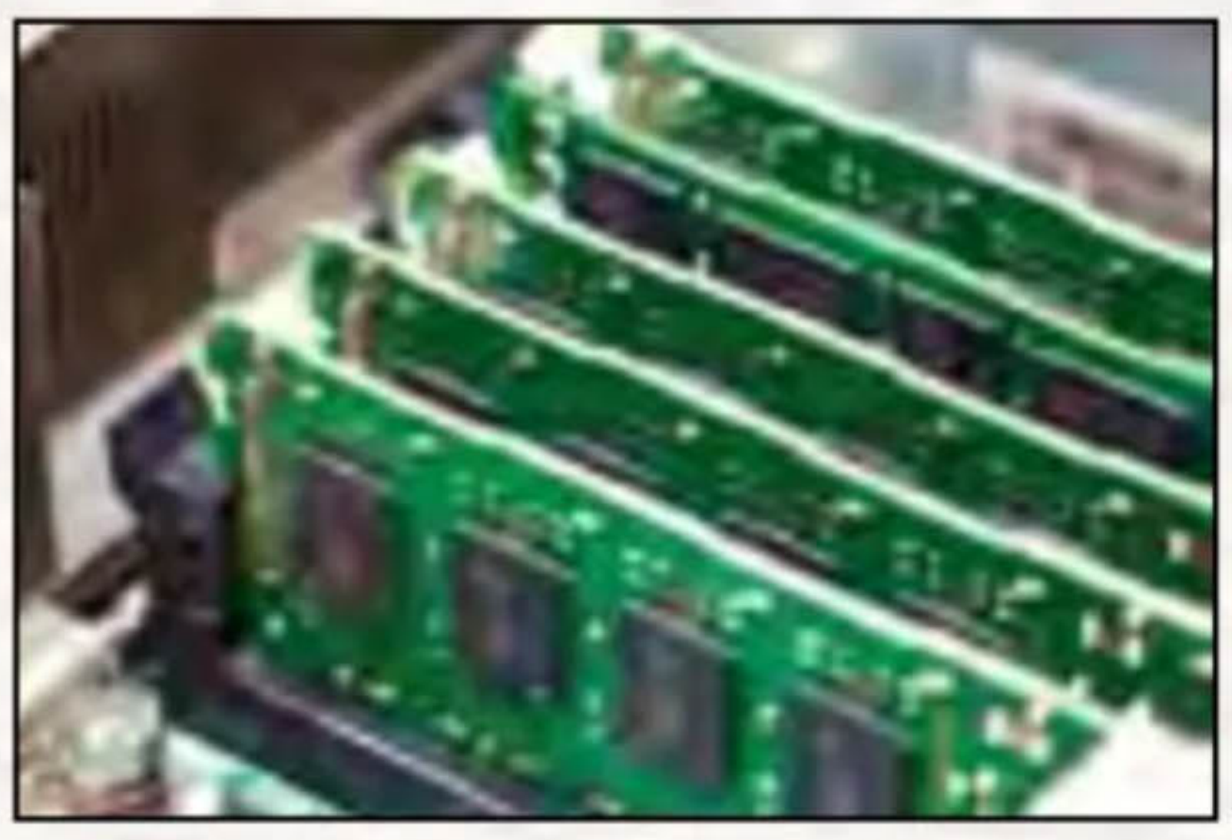

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January 2024
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A big thank you to the PE writers!

It's the end/beginning of another year, and so it's time for my annual salute to the *PE* contributors. I've said it many times before, and I'll say it again, *Practical Electronics* is nothing without its magnificent writers. They work hard every month to bring you the best in original content. So – in absolutely no particular order – a great big 'thank you' to Alan Winstanley, Mike Tooley, Ian Bell, Mike Hibbett, Clive 'Max' Maxfield, Phil Boyce, Julian Edgar, Barry Fox, Jake Rothman, and new kid on the block, Robin Mitchell. Also, a well-earned round of applause for the hard-working 'back-office boys', Stewart Kearn, Alan Winstanley and Kris Thain, who keep the shop and website ticking over.

Wireless for the Warrior

Many of you have been asking when the quartet of *Wireless for the Warrior* books will be back in stock – well, the answer is right now. All four are available, but selling at quite a brisk trot. They really are unique books and the perfect gift for anyone fascinated by vintage military communications equipment.

One important point for international purchasers – they have become very expensive to ship, so please send us an email before placing an order so that we can quote you the correct postage. The online shop cannot do that – it's just too complicated to implement accurately.

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From all of us at *Practical Electronics*, thank you for your support over 2023, have a very happy Christmas and a healthy 2024!

Matt Pulzer
Publisher

Oscillating onions, Batman!

Techno Talk

Max the Magnificent

The thought that we are now capable of creating multi-billion-transistor semiconductor devices with structures whose sizes are measured in billionths of a meter makes my eyes water. I'm too young for all this excitement!

In my previous Techno Talk column (*PE*, December 2023), I cogitated on the concept of Precision Time Protocol (PTP), a.k.a. IEEE 1588, used to synchronise the nodes forming a packet-based network with an accuracy in the sub-microsecond range.

The way this works is that somewhere in the network is a grandmaster clock – which typically obtains its time from some GNSS (global navigation satellite system) source – that propagates its concept of time throughout the network. One thing we didn't discuss was the fact that each node in the network maintains its own local time-of-day (ToD) value, as part of which it employs an oscillator, but what sort of oscillator might it employ?

Oscillating onions, Batman!

To be honest, there are more layers to this onion than you might imagine. We start with a resonator, which is a passive device, such as a quartz crystal, that vibrates at a fixed frequency (its resonant frequency). The next step up is an oscillator, which is an active device that combines a resonator with an oscillation circuit to generate a clock signal. The first quartz-based crystal oscillator (XO) was built by Walter Cady in 1921, more than 100 years ago as I pen these words.

Now, this is where things get interesting. The typical frequency stability variation over temperature of quartz-based XOs is between ±10 and ±100 parts-per-million (ppm). This isn't too shabby and will satisfy a wide variety of use cases, but it's insufficient for many of today's more demanding applications. The next step up are TCXOs (temperature-compensated crystal oscillators), which typically have frequency stability of ±0.05 ppm to ±5 ppm over their operating temperature range.

For those who demand even more, we have OCXOs (oven-controlled crystal oscillators) that achieve high stability by encasing the crystal along with temperature-sensing and compensation circuits inside a heated metal enclosure to create a miniature 'oven' with a relatively constant temperature. In this case, we can achieve frequency stability in the range of ±0.5 to ±20 parts per *billion* (ppb).

Ovens don't cool things down

When you think about it, an oven can only heat things up (it can't cool things down). This means the inside of the OCXO's oven must be maintained at a higher temperature than the outside ambient temperature ('duh'). What does this mean in these days of climate change in which a temperature of 40.3°C was recorded at Coningsby, Lincolnshire, on 19 July 2022 (a temperature of 53.9°C was recorded in Death Valley, California, on 16 July 2023)?

Well, fear not, because we are talking about oven temperatures around 75°C. If the outside temperature ever exceeds this value, keeping accurate time will be the least of our problems.

A rose by any other name

The first quartz-based OCXO was created in 1929 and this legacy technology is still ticking along (pun intended) to this day. Having said this, although quartz resonators remain the mainstay of the oscillation industry, devices using other materials – such as ceramic resonators or MEMS (micro-electromechanical systems) – are becoming increasingly common.

Theoretically, oven-controlled MEMS-based oscillators should be called OCMOs, but that's one battle no one in the industry appears prepared to fight. Instead, they refer to these bodacious beauties as MEMS OCXOs, and I cannot find it in my heart to fault them.

The reason I'm waffling on about all this is that I was recently chatting with the folks at SiTime. These little scamps have just introduced their Epoch MEMS OCXOs, which are truly OCXOs for the 21st Century. These silicon-based devices – which have a frequency stability of 1 ppb and an internal oven temperature of 95°C – are claimed to be eight-times more consistent, two-times more resilient, use three-times lower power, 30-times more reliable, and 25-times smaller than their legacy quartz-based OCXO counterparts.

How low can we go?

The term 'technology node' (a.k.a. 'process technology,' 'process node,' or just 'node') refers to a specific semiconductor manufacturing process. The first ASIC I designed deep in the mists of time we used to call 1980 was a device at the 5-micron (5µm) technology node.

In those days, depending on who you were talking to, the numerical qualifier referred to the width of a track or the length of the channel between the source and drain diffusion regions of a field-effect transistor (FET). I typically think of this number as reflecting the size of the smallest structure that can be created in or on the surface of the silicon chip.

Every time we move to a new technology node, we either *reduce* the area used or *increase* the number of transistors that can be squeezed into the same area. We also *increase* the speed of the transistors while *reducing* the amount of power they consume.

We started creating devices at the 1µm technology node circa 1985, where 1µm is 100th the diameter of a human hair (assuming a human hair has a diameter of 0.1mm). At that time, the naysayers started to proclaim that we were reaching the limits of what was possible. But we kept on overcoming problems and coming up with new solutions, and we started to describe nodes in terms of nanometres (nm).

I remember the progression well: 800nm in 1987, 600nm in 1990, 350nm in 1993, 250nm in 1996, 180nm in 1999, and 130nm in 2001. Surely this was as low as we could go… but no! We saw 90nm in 2003, 65nm in 2005, 45nm in 2007, 32nm in 2009, 22nm in 2012, 14nm in 2014, 10nm in 2016, 7nm in 2018, and 5nm in 2020. Apple's latest processor, the M3 is built with 3nm technology – it's most advanced version, the M3 Max, boasts 92 billion transistors. TSMC, the Taiwanese world leader in chip fabrication plans on introducing its 2nm node in 2025/2026, and pundits are predicting the 1nm node in 2028. (For comparison's sake, the atomic radius of silicon is 0.132nm, so we are talking about structures just a few times bigger than the atoms used to build them.)

All I can say is the thought that we are now capable of creating multi-billion-transistor devices with structures whose sizes are measured in billionths of a metre makes my eyes water.

Win a Microchip PIC-IoT WA Development Board

Practical Electronics is offering its readers the chance to win a Microchip PIC-IoT WA Development Board (EV54Y39A) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The PIC-IoT WA Development Board combines a powerful PIC24FJ128GA705 MCU, an ATECC608A CryptoAuthentication secure element IC and the fully certified ATWINC1510 Wi-Fi network controller, which provides the simplest and most effective way to connect your embedded application to Amazon Web Services (AWS). The board also includes an on-board debugger and requires no external hardware to program and debug the MCU.

Worth $45.50 (approx £37.50) each

The PIC24FJ128GA705 is a 16-bit microcontroller featuring up to 128KB of ECC Flash, 16KB of RAM and eXtreme Low Power. It has a 12-bit ADC operating at 200ksps with up to 14 analogue inputs, 3 comparators and CTMU for touch applications.

Available in 28-pin, 44-pin and 48-pin packages. This family is ideally suited for general-purpose applications.

Out of the box, the MCU is preloaded with firmware that enables you to quickly connect and send data to the AWS platform using the on-board temperature and light sensors. Once you are ready to build your own custom design, you can easily generate code using the free software libraries in MPLAB Code Configurator (MCC).

The PIC-IoT WA Board is supported by MPLAB X IDE and features the following elements:

- The on-board debugger (PKOB nano) supplies full programming and debugging support through MPLAB X IDE. It also provides access to a serial port interface (serial-to-USB bridge) and one logic analyser channel (debug GPIO).
- The on-board debugger enumerates on the PC as a mass storage interface device for easy 'drag and drop' programming, Wi-Fi configuration, and full access to the microcontroller application Command Line Interface (CLI).
- A mikroBUS socket allows expanding the board capabilities from a selection of 450+ sensor and actuator options.
- A light sensor used to demonstrate published data.
- Microchip MCP9808 high-accuracy temperature sensor used to demonstrate published data and MCP73871 Li-Ion/LiPo battery charger with power path management.

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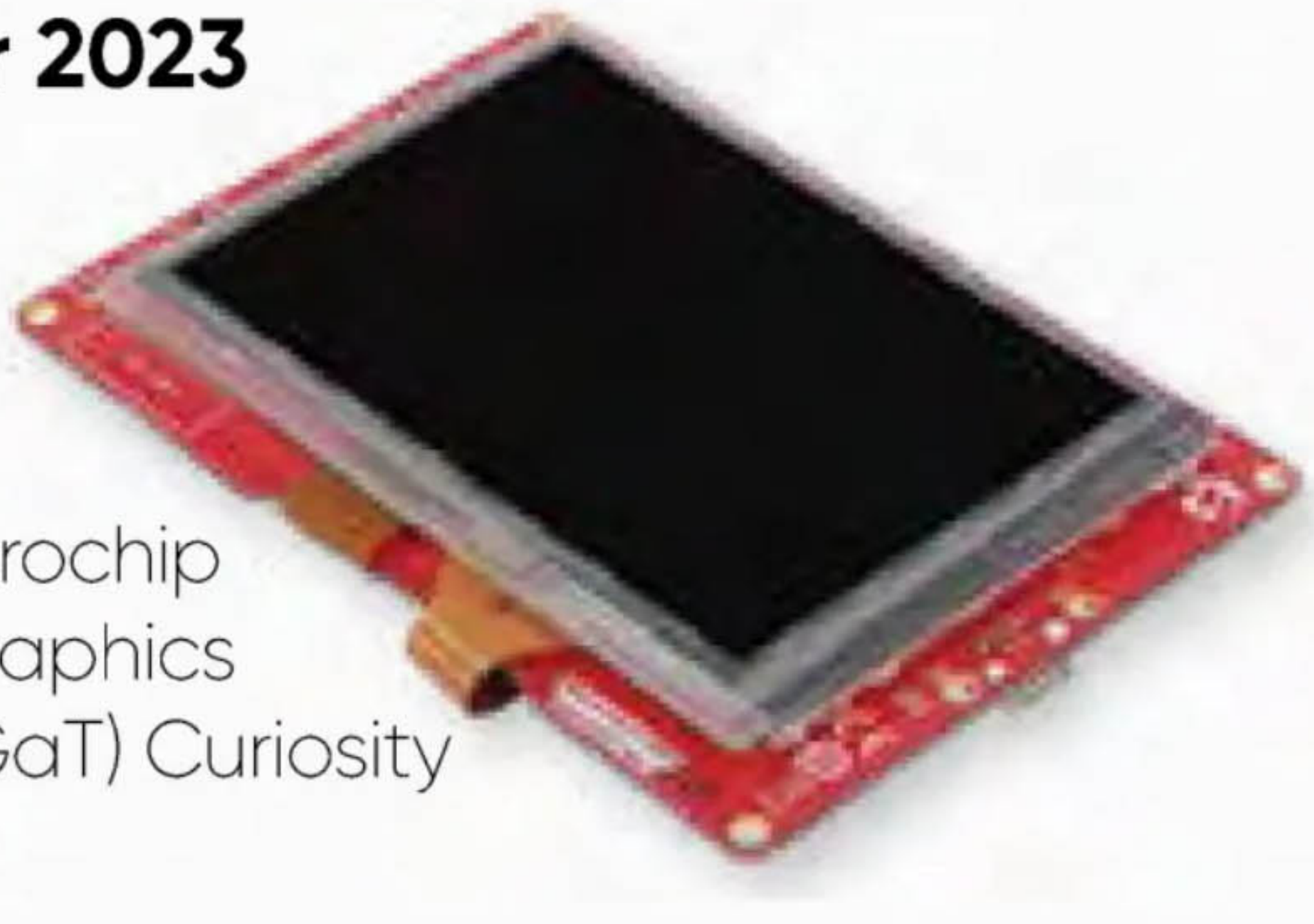
The closing date for this offer is 31 December 2023

September 2023 winner

Ben Woods



He won a Microchip Integrated Graphics and Touch (IGaT) Curiosity Evaluation Kit

Net Work

Alan Winstanley

This month's column goes in search of vampires – not the blood-sucking variety, but the electrical power-consuming type. For the enlightenment of our many overseas readers there's an insight into the mysteries of the British mains plug, plus Alan discovers more uses for his Ecowitt Wi-Fi weather station.

Last month's Net Work column had a power-related theme, suggesting a compact power supply in the form of a 12V mains adaptor that, thanks to its built-in Li-Ion battery, would enable a router, IP camera or similar smaller device to continue operating during mains power cuts. I also explained how the UK's electricity distribution network is divided into 'Rota Load Blocks' and how you could check the coverage of your own block using an interactive map on the 105 website: **www.powercut105.com**

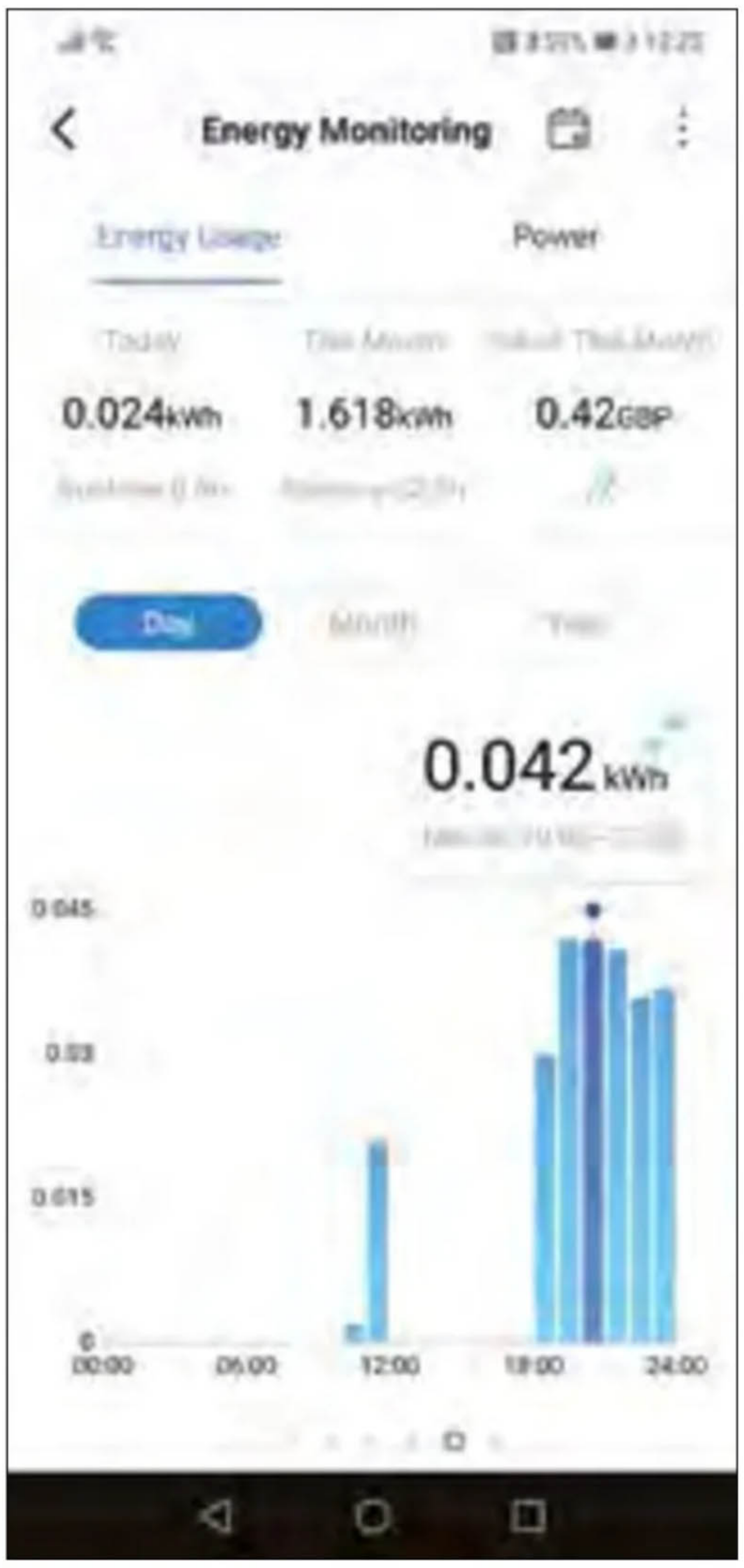
In today's economic climate, saving energy (and money) is more important than ever, so I've been using a plug-in power meter to check the energy consumption of various electrical appliances dotted around the house. As I explained last month, I've already unplugged or discarded some legacy electricals which will knock £100 or more per year off the fuel bill, and I've been surprised to find how some supposedly benign electrical appliances are actually wasteful 'money sinks', sometimes called 'vampire appliances' because they silently sink their teeth into electricity and cost you hard cash even when they're not in use.

As a rule of thumb, something consuming six watts on standby 24 x 7 will swallow one UK electrical unit or kWh a week, costing about 30p, adding up to £15 a year at current UK prices. In electronics, we're often eager to know a circuit's quiescent current but when it comes to household electrical appliances, something that's rarely highlighted by manufacturers is a product's *standby* power. It's typically buried on the back page of a user manual or PDF somewhere, so you have to dig deep to discover how much electricity an appliance is using when it's doing nothing useful at all – just being 'on', even if it's only 'standby mode'.

Some empirical tests with my digital power meter uncovered a few surprises: I found a remote-controlled tower fan, when on standby (which is most of the year), silently consumed nine watts of electricity or £23 a year; an old clock-radio cost about the same, as did an ultrasonic pest repeller as well as a coffee pod machine. Disconnecting or scrapping these items will save about £100 a year alone at current prices. I found a 300W electric blanket still drew 12 watts on standby (£30 a year, pro rata), while a small 1kW kettle with digital controls was found to use 7-9W on standby, or another £20 or so annually for doing absolutely nothing.

That's entertainment

On the home entertainment front, I was gratified to find a Humax PVR only drew a watt or two on tickover, while



TP-Link's Tapo smartphone app displays power and usage data for electrical equipment connected to their TP110 smart socket.

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A plug-in power meter like this Ketotek model offers an insight into an electrical appliance's running costs. Available from Amazon.

a Panasonic Blu-Ray DVD player drew negligible standby power provided I disabled the 'Quick Start' option. I found a Chromecast dongle used 3W (say £8 a year) while a Devolo PLC Wi-Fi/Ethernet adaptor supposedly has an auto power saving mode that switches it down from 9W to 1W, but it seems pretty warm all the time; perhaps the Chromecast keeps it awake, hence it consumes more power. Meanwhile the TV set is connected to the mains through a TP-Link Tapo smart socket that's on extended test (see *Net Work*, December 2022), and an Amazon Echo Show 8-inch LCD display (itself using a 30W power supply) controls this with a few voice commands.

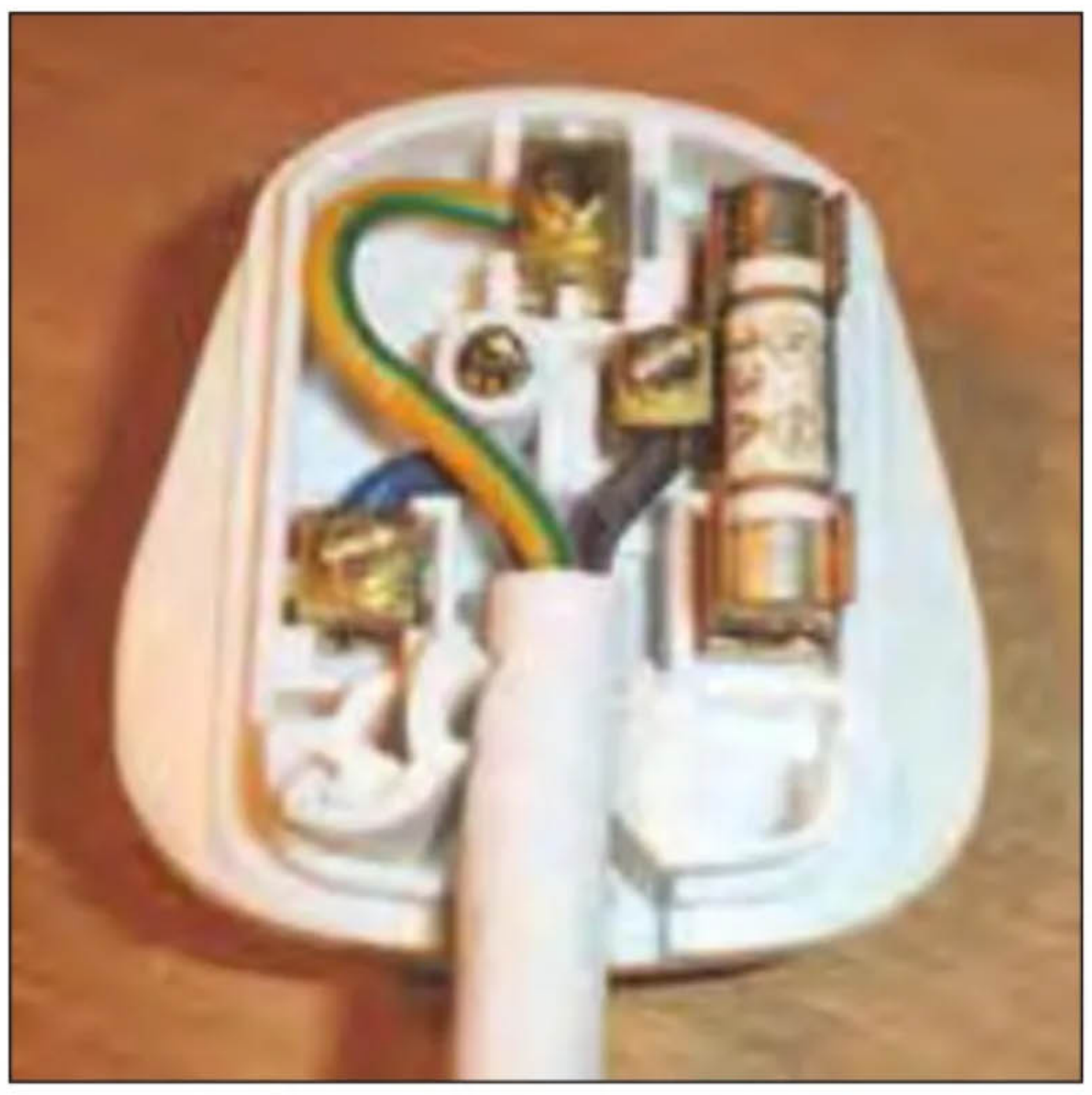
Usefully, an energy monitoring feature is included with the Tapo P110 smart socket. It can also be managed through an app, and by tapping in your electricity tariff, the running costs and usage of connected equipment can be displayed. The app tells me that the TV has used 67kWh so far this year (£20). Incidentally this smart socket also has a useful time switch and an 'Away' mode, that switches, for example, a light on and off randomly. Choose carefully as other Tapo sockets (the Tapo P100) come *without* this energy monitoring feature.

Plug-in power meters are readily available from the usual websites for as little as £6. A backlit LCD type makes life easier, but reviews of cheap identical-looking white-label Chinese devices are very mixed, so maybe treat those as consumable items. Worth considering (not tested by the author) would be the upgraded backlit version of the pricier KETOTEK Power Meter Plug (Amazon UK, item B0BZYN6544) which also shows VA, frequency and power factor and other data. Finding and clobbering those 'vampire appliances' is quite a rewarding exercise, for ourselves if not the utility companies – and furthermore, no vampire-repelling garlic, silver crosses or wooden stakes are required!

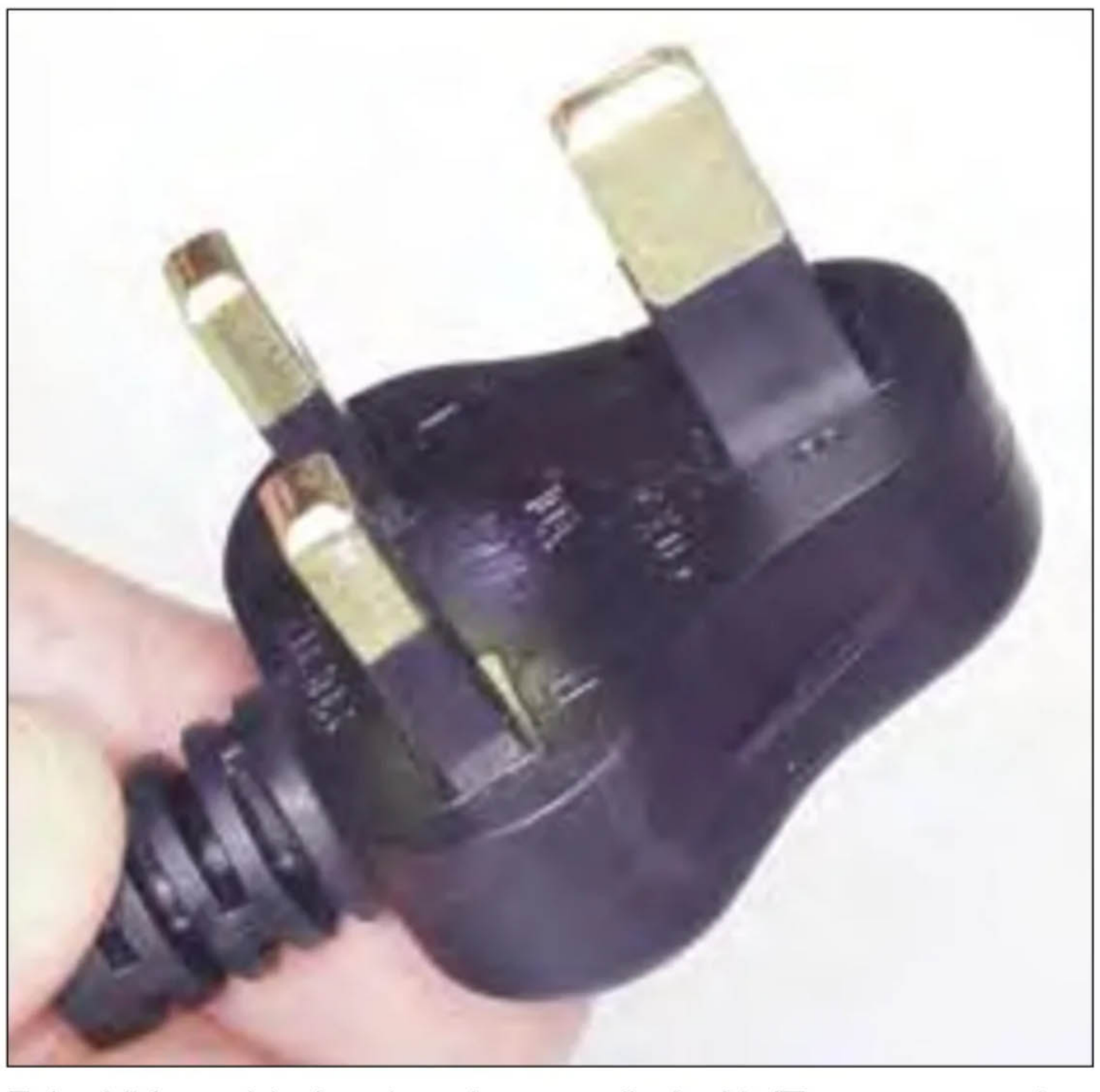
Getting plugged in

Still on the topic of connecting electrical equipment and saving money, one everyday piece of hardware familiar to us all, or so I thought, is the mains plug. I discovered in a forum that many American constructors and electricians had never come across the British mains plug and, when compared with US two-prong types, the British one seemed huge, clunky and grossly over-engineered (all true). Our so-called 'Type G' plugs (also called 'plug tops' in Britain) also appear in a few overseas countries, and it's generally recognised that the British BS1363-standard 13A plug design is the best mains plug in the world, bar none. It has several key safety features including sleeved live and neutral pins to safeguard against fingers curling underneath when it's being inserted, and a longer earth (ground) pin that ensures that the apparatus is grounded before the mains supply itself is connected.

Every British plug has a hidden surprise because it contains a 1-inch colour-coded ceramic cartridge fuse, red for 3A, black for 5A and a brown one denoting a 13A fuse, suitable for appliances consuming up to 3kW. My photo shows the interior of a typical plug. What's less obvious is the reason for the fuse in the first place. It 'oversees' the mains power cord rather than simply protecting against appliance faults or overloads. Such a fuse is needed because of the British way of installing 'ring' mains wiring, daisy-chaining one outlet to the next as part of a loop, rather than using a radial design. The plug's fuse will disconnect the mains supply if, say, you slice through the cable accidentally; without a fuse, consumers would rely on the main circuit breakers (say 32A) in the residential fuse box, creating a fire hazard. Believe it or not, double-insulated equipment, which needs no earth, sometimes comes fitted with a 3-pin plug that has a plastic earth pin!



Inside a typical British 'Type G' mains plug, fitted with a ceramic cartridge fuse and cable grip.



Fake UK moulded mains plug supplied with IT gear sourced on the web. Note unsafe shrouded earth pin and lack of fuse.

The British mains wall outlet also has two key design features: a sprung shutter that only opens when the plug is pushed in (which is why the plug's earth pin is longer), and (often a surprise for visiting Americans) wall outlets that have an on-off switch. Some of my outlets, located in dark corners, also have power-on neon lights. A deep freezer or aquarium might be connected to an outlet that has no switch, though, to prevent it from being accidentally switched off.

Today's generation might be dumbfounded to learn that, until the 1990s, hardly any electrical gear bought in Britain came with a mains plug, so you had to fit your own, stripping the insulation to the right lengths and wiring them correctly to the three terminals, sorting out the cable grip and fuse along the way. Until factory-fitted plugs were mandated by law, householders grappled with $P = IV$ to figure out which fuse

This traditional good-quality British-made mains plug had a built-in neon indicator. The BSI 'Kitemark' logo signifies testing and compliance with relevant British Standards.

Two types of foreign-made UK plugs with rocker switches and power indicator, sourced online. The one on the right looks neater, but it does not have a compliant 1-inch ceramic fuse.

rating to use, mindful of the product's power consumption. No doubt there were countless instances of electrical fires or accidents (or worse) caused by the incompetent fitting of electrical plugs.

False economies

Another reason that fitted plugs became compulsory was that poor quality, counterfeit types were sold that were clearly hazardous. Unfortunately, fake plugs are still seen today on low-grade imported goods sold online, often bundled with mains power packs. They are instantly recognisable as being small mouldings with no fuse, or having insulation covering the ground pin as well as live/neutral. The cable insulation can sometimes be stripped off between finger and thumb, the wire cores themselves may be steel wire, and any BS 1363 (British Standard) or CE marks will be fake as well. They should be thrown away in electrical waste, after cutting off the plug.

One thing you won't find anywhere these days is a mains plug with a simple neon or LED pilot light, such as the traditional BSI 'Kitemarked' type shown in my photo. These were handy reminders that something was switched on, but they fell by the wayside many years ago.

Back to my energy-saving topic: to save electricity, vampire devices can be unplugged or switched off at the wall socket, but if they share, say, an extension lead (power strip) with other always-on equipment instead, then one option is to use a mains plug with built-in rocker switch and, usually, a neon or LED indicator. A large plug, moulded in black or white, seems to be the only one widely available and these are sold online. They are onerous to wire up but they just about do the job.

Surfing around, I spotted a neater-looking UK-style plug with built-in rocker switch and LED, originating from China. They seem impossible to come by as far as UK sales are concerned, so I suspect they are intended for Asian markets such as Singapore. One reason might be that the fuse carrier holds a 20mm type rather than a standard 1-inch cartridge fuse. Even so, I'm tempted to use them on small appliances – my photo shows examples of both of these plugs.

Another option is to find a power strip having individually switched sockets for ultimate control and, unusually, a small number made by Brennenstuhl also have cable exits at either end for convenience – see the data sheet at: **https://bit.ly/pe-jan24-bren**

Last, an interesting energy-saving socket is produced by Ansmann that isolates an appliance completely one minute after it goes into standby mode. The Ansmann AES-3 uses zero standby power and can be restarted by pressing a 1.8m corded button. A zero-watt countdown timer, the Ansmann AES-1 switches off after 15m / 30m / 1hr / 2hrs /4hrs or 8hrs in case you forget to switch an appliance off. These money-saving products are sold by all the major online electronic retailers.

Readers who would like to learn more about the evolution of British plugs and sockets will find lots of interesting details at: **https://bit.ly/pe-jan24-ukplug**

There's an excellent explanation of worldwide electric plug standards at: **https://bit.ly/pe-jan24-plug**

An alphabet of storms

With winter firmly upon us, Britain's weather system has entered its stormy season as Atlantic weather fronts batter the country with gales, rain and floods. In 2015 the UK's Meteorological Office joined their Irish and Dutch counterparts in giving major storms some beguiling names, and an A-Z list of names is agreed upon annually. You can suggest a name yourself, and the full list and timetable is published by the Met Office at: **https://bit.ly/pe-jan24-met**

Storm Babet in October caused a few problems in Britain, including at the non-working isolated farm where the author lends its owner a helping hand. Babet blew down an overhead power line

The Ansmann AES-3 is a zero-power standby shutdown switch with a restart button on a 1.8m cord.

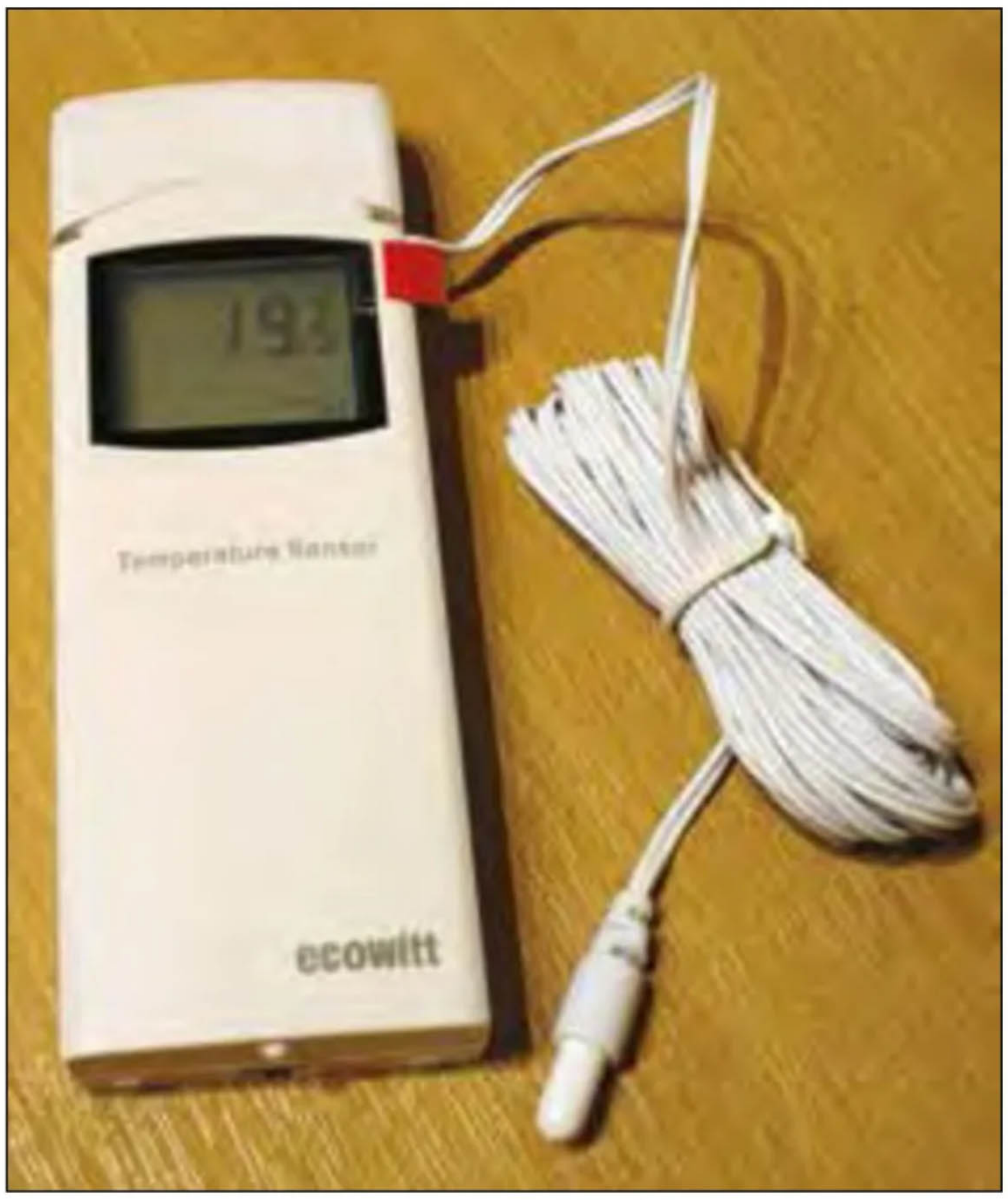
which blacked out the farm, taking the farm's telephone system with it. As the farm relies on cordless big-button phones that have no battery backup, when the power goes off, the base station stops working so the phones are cut off as well.

For reasons explained in earlier columns, the farm's residents have no need for broadband and can't be expected to use a mobile phone either, let alone grapple with a smartphone full of apps. Forget all about email, WhatsApp or even text messaging! Eventually, another cottage owner called me, and I duly headed out in the rain, only to find live power lines strewn across rain-soaked hedgerows on both sides of the country lane. I could think of better ways of spending my milestone birthday, I mused, but I set about calling the power authorities on '105' and we were grateful to have power safely restored later that evening. As a workaround in the farm's 'digital desert', I returned with an old analogue phone and plugged it into the farm's BT phone socket as a standby, which can only help in case the power goes off again. An LPG cooker is also installed so we'll get by somehow, as we run through the alphabet of storms.

Action weather stations!

As I write this piece, Storm Debi has just been announced by the Met Office and regular readers will recall that I've been using an Ecowitt HP2551 weather station since the start of the year. I've enjoyed comparing weather forecasts with actual events recorded by my own set-up. I can also tell if there's been a frost or whether it's rained in the night, at what time and how much. The indoor TFT colour display is crystal clear and the outdoor 868MHz-based sensor array, lashed firmly to a concrete post in the garden, has performed perfectly so far. I've had no problems with communications apart from a brief interruption caused by my own Wi-Fi going down, and the Ecowitt website and smartphone app have been commendably trouble-free too, uploading and displaying the data captured by the various weather sensors. Overall, I've found it a very rewarding experience so far, with nothing to dislike at all.

Bundled with the weather station is a single stand-alone transmitter (type WH32A) that displays temperature, humidity and barometric pressure on its LCD. This data is the 'Indoor' readings seen on the main console, while the outdoor array transmits wind, rain, solar, temperature and humidity data. This model also has a multi-channel operation which accepts data from up to eight external wireless sensors that can monitor conditions in various locations. The main display can scroll through these sensor readings automatically, in a multiplexing fashion, and data can be read on the smartphone app or uploaded to the cloud. (You can keep your Ecowitt website data and location private, or share it using links or a QR code: this works really well.)



The Ecowitt WN30 sensor has a waterproof temperature probe on a 3m cable, designed for their Wi-Fi weather stations or gateways. Its dip switches have been set to show °C and use channel 4.

Freezer meltdown

A wireless transmitter (type WH31 or WN31A – same thing) is sold separately which displays temperature, humidity and channel number on its LCD. Adding a new sensor is commendably hassle-free: it merely involves setting the desired channel (1-8) and scale (°C/°F) and fitting some batteries. The main console detects the new sensor without a problem. These sensors are not weatherproof though, and should be sheltered from the elements. Unfortunately, the dip switch settings printed in the manual are actually upside down compared with the correct ones shown on the plastic case!

The multi-channel feature of the Ecowitt weather station gave me another idea – how about an in-home monitoring system as well? Some time ago, the author's Samsung deep freezer suffered a calamity when the refrigerant leaked – while the freezer's digital display showed –18°C on the door as normal, it turned out that this was only the 'set point', and the freezer interior was silently thawing out, reaching +5°C, resulting in an expensive total loss. Apart from the self-contained WN31A transmitter already mentioned,

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Ecowitt's GW1100 Wi-Fi weather station gateway uses their range of wireless sensors to display data on a web page or smartphone app instead of an LCD console.

Ecowitt produces one with a waterproof (IP65) wire probe sensor (WN30) that is fitted with a 3 metre cable terminated in a probe. The temperature range is quoted as −40°C to +60°C (−40°F to +140°F). This offers the prospect of wirelessly monitoring, say, a fridge or deep freezer, checking a horticultural propagator, water tank, aquarium or terrarium, or measuring soil or water temperature. I learned that other customers are indeed using Ecowitt transmitters to monitor refrigerators, attics, loft spaces and basements this way. You can rename the various sensors to something more meaningful on the main console (eg, 'Pond', 'Freezer', 'Attic', 'Greenhouse' and so on) and the weather station can ultimately be set up to send email alerts or sound an alarm, though the console's built-in piezo alarm is quite timid.

I now have five wireless transmitters monitoring their environment, but if you don't need an all-singing and dancing LCD weather station, Ecowitt offers a smaller Wi-Fi gateway, the GW1100 which uses a smartphone app instead. It is 5V USB rechargeable. The comprehensive accessory range includes a floating pool thermometer (for fishpond keepers), a soil moisture probe, a pricey PM2.5 particle sensor, lightning detector, water leakage sensor and a leaf wetness sensor – all equally compatible with the larger weather station. A very useful sensor compatibility table is at: **https://bit.ly/pe-jan24-eco**

Many of these items are sold online by Amazon, but the prices do vary wildly; I recently spotted the HP2551 for just over £170 all in, but I have seen it listed at £100 more than that, so my previous advice remains – monitor prices very closely and use the 'Cameliser' web browser plug-in to alert you to price drops. Ecowitt accessories are also sold on AliExpress, and I recently bagged a WN30 and WN31 transmitter, a spare anemometer wind cup and a debris guard for the rain gauge, all at less than half price. It seems that AliExpress and China's Temu are slugging it out for trade: if you have an AliExpress account, try logging into AliExpress using a different email address and see if new-user discount offers pop up. Remember that VAT will be added to the dollar prices shown. The UK website is also worth a look: **https://weatherspares.co.uk**

That's all for this month – remember that the above hyperlinks are ready-made for you to click on in the *Net Work* blog on our advert-free website at **electronpublishing.com**, which also has a special page for each month's free-to-enter Microchip competition. See you next time!

The author can be reached at:
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This series of articles provides a broad-based introduction to choosing and using a wide range of test gear, how to get the best out of each item and the pitfalls to avoid. It provides hints and tips on using, and – just as importantly – interpreting the results that you get. The series deals with familiar test gear as well as equipment designed for more specialised applications.

The articles have been designed to have the broadest possible appeal and are applicable to all branches of electronics. The series crosses the boundaries of analogue and digital electronics with applications that span the full range of electronics – from a single-stage transistor amplifier to the most sophisticated microcontroller system. There really is something for everyone!

Each part includes a simple but useful practical test gear project that will build into a handy gadget that will either extend the features, ranges and usability of an existing item of test equipment or that will serve as a stand-alone instrument. We've kept the cost of these projects as low as possible, and most of them can be built for less than £10 (including components, enclosure and circuit board).

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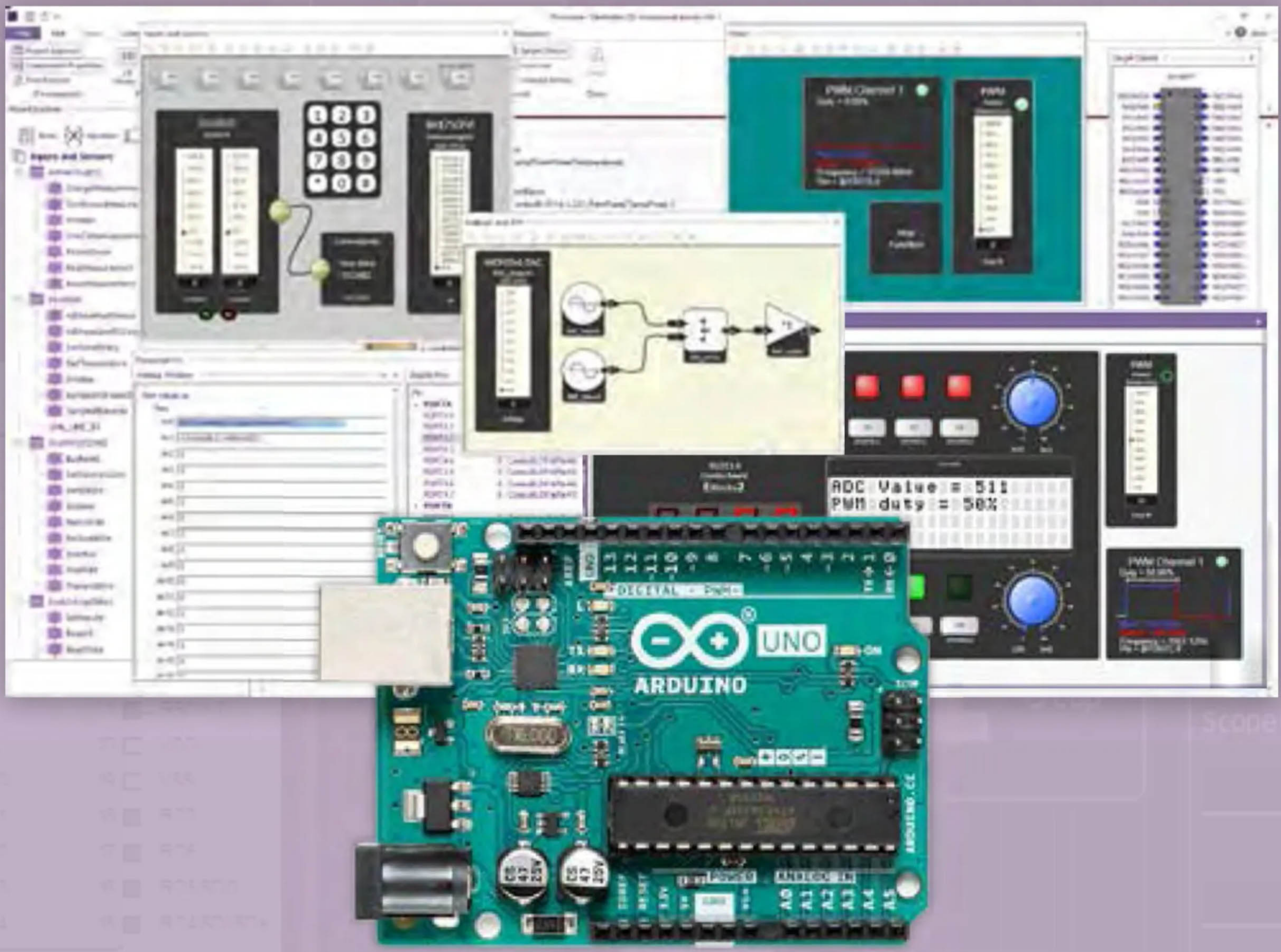

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The Fox Report

Barry Fox's technology column

Project challenges for inventive PE readers

This month, I humbly offer creative readers two practical test problems which are crying out for DIY project solutions.

The suggestions flow from my recent experience of rebuilding a home AV system, by replacing the main amplifier. This involved ripping out and re-connecting a jungle of wires, while simplifying the set-up by removing redundant components.

A few simple rules...

Rebuilding any AV system is a lot easier if you follow a few simple practical guidelines, not all of which will be as egg-suckingly obvious to others as they are to some. Some of these guidelines date back to invaluable tech training I received in the RAF.

Take your time – one labelled wire at a time

Wherever possible, disconnect only one wire or pair of wires at a time. Identically label each end of each wire. There are not enough colours in the rainbow to colour code every connection path. I use a Dymo label computer printer with Dymo software (but cheaper compatible label cartridges bought on line) to print simple stick-on labels for each end of each cable run.

Use cable ties – gently

Modern 'handcuff' cable ties are great for tidily binding cables together, to stop self-tangling. But don't over tighten or you won't be able to identify troublesome wires by gently tugging one end and watching for movement elsewhere.

Check cables

Flat digital HDMI and Ethernet cables are now available. They hide neatly under rugs, but they love to twist themselves and treading on the twist can cause faults. A £10/20 battery-powered two-part continuity tester is an essential tool for checking if a digital cable has gone bad.

Avoid the 'touch' test

Optical SP/DIFs can be identified by looking for the telltale red laser light. Checking and identifying low-voltage audio cables can of course be done by touching to induce mains hum. But if the amplifier volume is up, there's a risk of blowing speaker cones. Touching wires is always best avoided. You never know when a dangerous voltage may have crept through.

Build a cable tester

Connecting a meter to small phono and coax plugs is tricky and for years I have been happily using an analogue cable test kit from Vision Products of Northampton. This uses a low-voltage transmitter and receiver that plug into cable ends to show a red LED for short circuits and beep for successful connection. These handy testers came with an assorted collection of plugs and sockets that connect to almost every imaginable analogue cable.

That's the good news – the bad news it that Vision Products informed me that unfortunately these kits are no longer available, and I can't find any other source. Perhaps someone would like to make this a construction project? It shouldn't too difficult.

(left) Testing a flat cable; these are vulnerable to folding/kinking, so lay them carefully

(right) Using the excellent, but sadly discontinued Vision Test Kit to check AV cables and plugs – can clever *PE* readers come up with a viable alternative?

Failing OLEDs

Whole batches of radios and Internet radios (for example, from British DAB pioneers Pure and Roberts) were built with OLED displays which are now failing. Without a means to see the settings and tuning options, otherwise perfectly good radios become unusable. This frustration is compounded by the fact that 'simply' replacing the display turns out to be tricky, expensive and more trouble than it is worth.

However, by chance I discovered that pointing a smartphone camera at the failing OLED display provides a much more readable image on the smartphone screen. With so many old smartphones now languishing in drawers, perhaps someone might rise to the challenge of designing an ageing-OLED viewer for equipment troubleshooting?

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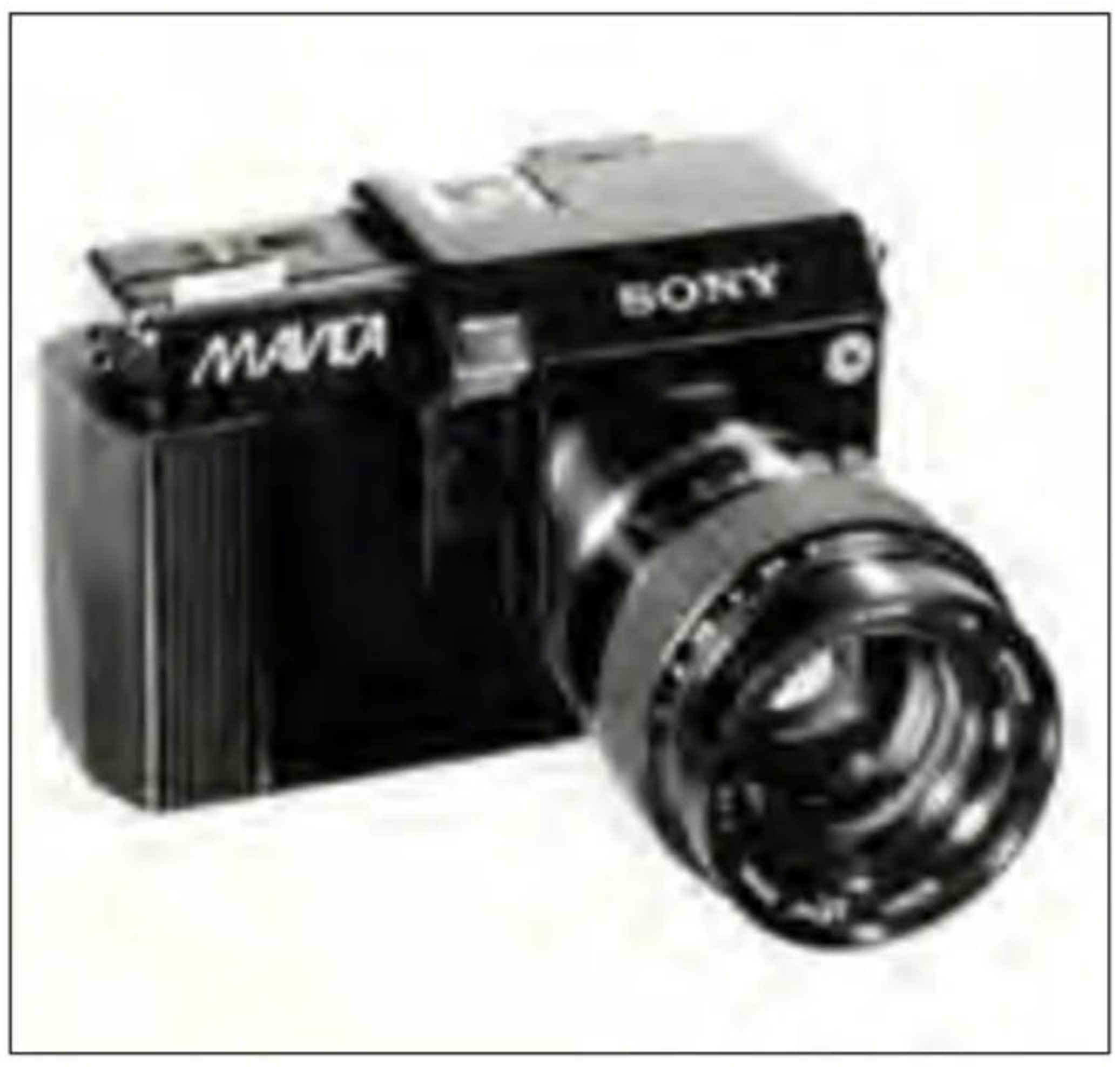
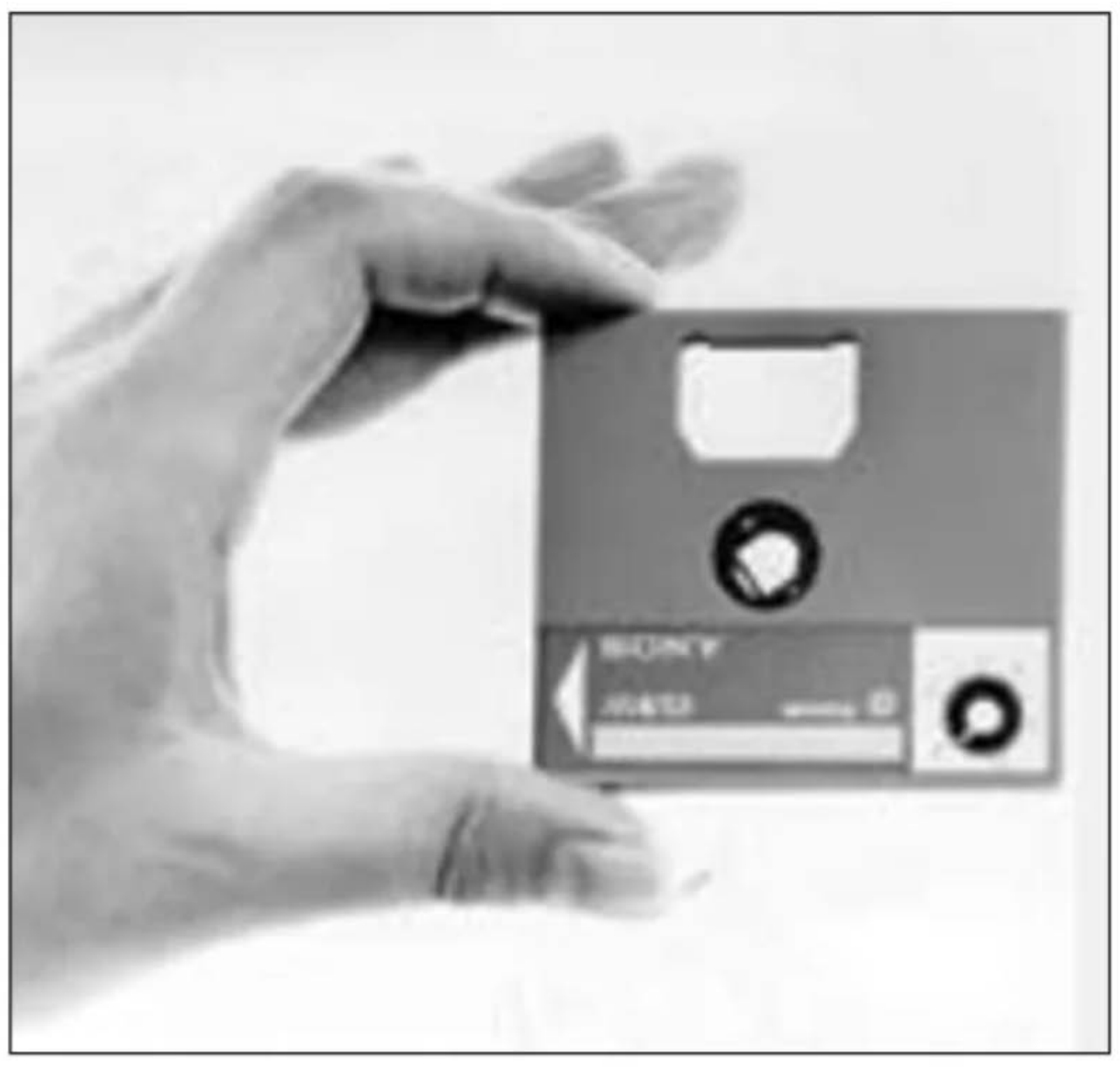
tekkiepix pic of the month
Mavica – Sony's pioneering digital camera



Sony's pioneering digital SLR Mavica offered a range of lenses.



Each Mavipak 5cm floppy disc stored up to 50 colour pics.

Sony obviously liked the name Mavica. In 1974 the company announced the Mavica video recorder, which captured moving pictures on flexible magnetic cards that measured 15 by 20cm, and curved slowly past a scanning video head.

Each card could store 10 minutes of colour TV with stereo sound. Sony promised higher density cards with increased recording time, but Mavica was killed by the arrival of Sony's own Betamax, with several hours recording time from a small cassette.

A sony digital first

In 1981, Sony dusted off the name and shocked the photographic world by demonstrating a camera, which looked like a conventional SLR (single-lens reflex), but contained an electronic image sensor and miniaturised computer disk recorder. The SLR Mavica recorded analogue TV stills on a 5cm floppy disc coated with pure metal powder and spinning at 3,600 rpm. The pictures replayed through a home TV.

In July 1988, 42 electronics and photographic companies agreed a standard for 'electronic still video'. Based on the NTSC TV standard. It gave either 25 fully interlaced picture frames, or 50 half-scan pictures of lower resolution. But the technology remained too expensive to rival film, so most companies shelved the idea.

Beaten by Fuji

In December 1988, Sony tried to go it alone, launching a consumer version of Mavica in Japan. The full kit cost around £500 and it bombed. By then Fuji had developed a prototype digital camera which used a solid-state memory card instead of disc, which is of course the way modern digital cameras work.

However, since memory cards were still expensive, Sony moved on to using a standard 9cm PC floppy to store 40 digital images at very low cost.

Practical Electronics is delighted to be able to help promote Barry Fox's project to preserve the visual history of pre-Internet electronics.

Visit **www.tekkiepix.com** for fascinating stories and a chance to support this unique online collection.

We've published numerous LC meters that can measure inductance and capacitance, but you might need to know the quality factor (Q) of an inductor, not just its inductance. This Q Meter uses a straightforward circuit to measure the Q factor over a wide range, up to values of about 200.

Inductor
Q = 112
Vo=154
C=162pF
Q
METER
L
C
LOW Q
HIGH Q
TUNE
CAP

Q Meter

By Charles Kosina

The history of Q Meters goes back to 1934, when Boonton developed the first Q Meter.

The Q Meter is a somewhat neglected piece of test equipment these days. Hewlett Packard bought Boonton in 1959 and produced revised versions of their Q Meter. Does anyone still manufacture them? It seems not. You can find a few on the second-hand market; but they fetch prices up to $3000. The HP 4342-A is an excellent unit and is a more modern version of the original Boonton design.

My Q Meter design can't come near the quality or accuracy of HP equipment. It is not designed as a laboratory instrument, but it will give Q measurements up to a value of about 200 with an accuracy of about 10%.

Q & A

So, what is Q, and why do we need to measure it? It is a measure of the dissipative characteristic of an inductor. High-Q inductors have low dissipation and are used to make finely-tuned, narrow-band circuits. Low-Q inductors have higher dissipation, resulting in wideband performance. It can be expressed as:

$$Q = 2\pi \times (E_{PK} / E_{DIS})$$

Where E_{PK} is the peak energy stored in the inductor and E_{DIS} is the energy dissipated during each cycle.

Let's consider two passive components, an inductor and a capacitor. The reactance of the inductor is $X_L = +j\omega L$.

Here, $j = \sqrt{-1}$, X_L is in ohms and $\omega = 2\pi f$ (f is the frequency). For example, a 10µH coil at 10MHz will have a reactance of +j628Ω.

A capacitor has a reactance of the opposite polarity, ie, $X_C = 1/{-j\omega C}$.

To resonate at 10MHz, the capacitor needs a reactance of –j628Ω, which equates to 25.3pF.

But inductors and capacitors are not perfect. A practical inductor can be approximated as an ideal inductor with a series resistor. The coil winding will also add a small capacitance across the inductor, as shown in Fig.1. The capacitor is also not perfect but generally has a much smaller inherent resistance, so for this calculation, we can assume it is.

The inductor's Q is defined as $Q = X_L/R_L$ and the -3dB bandwidth of such a tuned circuit is BW = f/Q.

So, a tuned circuit with a 10µH coil and a Q of 100 would have a -3dB bandwidth of 100kHz at 10MHz. The Q is important if you're trying to design something like a bandpass or notch filter.

In Fig.2, we have a series-tuned circuit fed by a variable frequency source with frequency f, voltage V_S

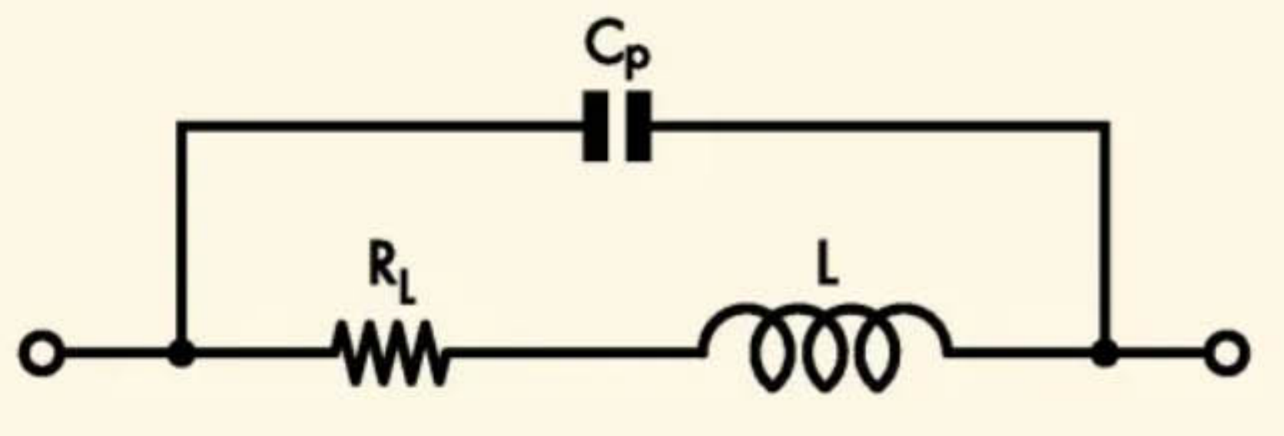


Fig.1: a real inductor does not just have pure inductance; it also has parasitic series resistance (R_L) and parallel capacitance (C_P).

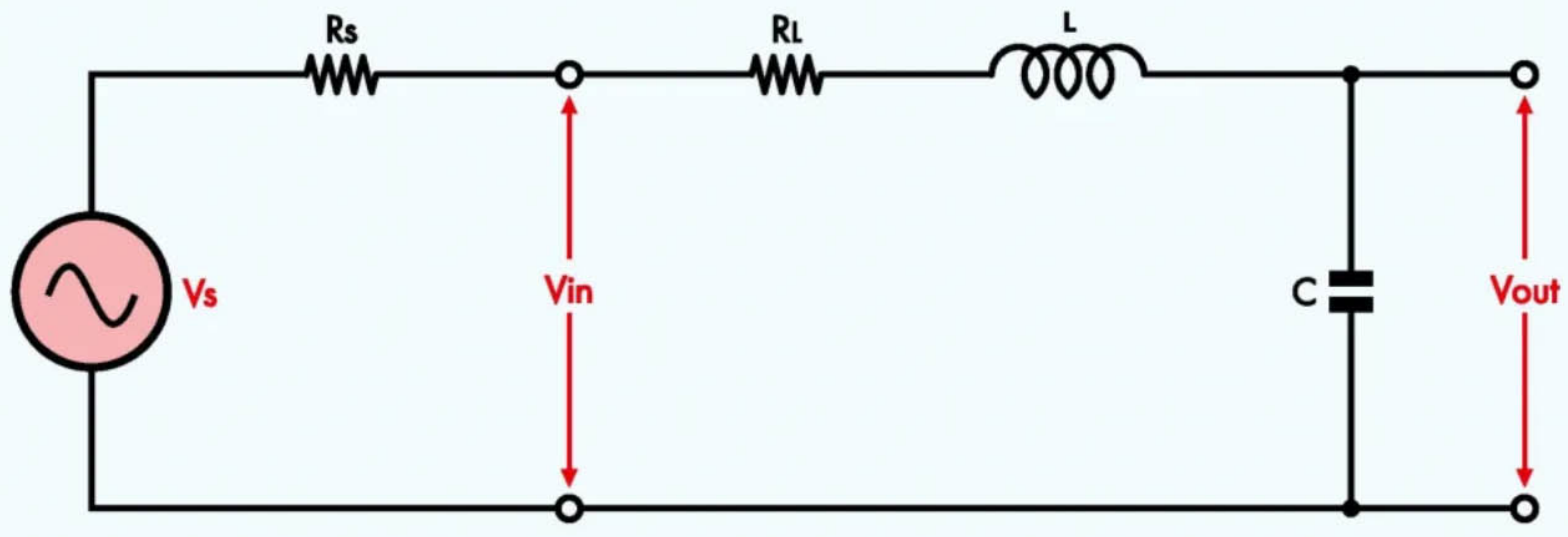


Fig.2: we can calculate an unknown inductor's Q (quality factor) using this circuit. It is connected in a series-tuned circuit with a capacitance, and that circuit is excited by a sinewave from a signal generator via a known source resistance. Measuring the input and output AC voltages and calculating their ratios allows us to compute the inductor Q, assuming the Q of the capacitance is high.

and source resistance R_S. At resonance, $X_L = -X_C$; in effect, a short circuit, so the load on the generator is $R_S + R_L$.

By having a generator with source resistance R_S much lower than R_L, the voltage measured at V_{IN} will be close enough to V_S. The current through the circuit will be $I_S = V_S/R_L$.

Therefore the voltage at the junction of the inductor and capacitor is $V_{OUT} = X_L \times I_S$. By measuring V_{IN} and V_{OUT}, the Q can be calculated as $Q_L = V_{OUT} / V_{IN}$. That assumes that the capacitance has been adjusted to achieve peak resonance with the inductance, ie, $X_L = -X_C$. That can be done by sweeping the capacitance until the peak V_{OUT} voltage is reached.

The first design challenge is to have an extremely low generator source resistance. If we have a 10μH coil with a Q of 100, at 5MHz, the effective R_L is 3.14Ω (314Ω/100). If our source resistance is 0.1Ω, that will give an error of about 1%. But at 1MHz, R_L becomes 0.628Ω, and this error blows out to 15%.

So using a higher frequency will generally result in a more accurate Q measurement.

Low source resistance

Boonton solved the source resistance problem by having the generator heat a thermocouple using a wire with a very low resistance, as shown in Fig.3. The voltage generated by this thermocouple was measured by a DC meter which indicated how much current was applied to a 0.02Ω resistor in series with the external inductor.

I have a Meguro MQ-160 Q Meter, essentially a 1968 version of the original Boonton 260-A design, using such a thermocouple and resistor. No transistors in this one; it's all valves!

But for our design, a thermocouple is not practical. The HP design eliminated the thermocouple and instead used a step-down transformer. The transformer is fed by a low impedance source, as shown in Fig.4.

If our source resistance is 50Ω, like the output of a typical signal generator, and the turns ratio is 50:1, the effective source resistance is 0.02Ω ($50\Omega/50^2$), exactly what we want. Unfortunately, it is not so simple as it implies a perfect transformer. Losses in the transformer core plus winding resistance conspire against us and push up the source resistance value.

We can improve this by feeding the transformer's primary from the output of an op amp, which has an impedance close to zero. In this case, a turns ratio of 10:1 is adequate as the resultant 100:1 impedance ratio will give an acceptable load to the op amp.

This is what I have used in my design. The transformer is a ferrite toroid of 12mm outside diameter. The primary is 10 turns of enamelled wire, while the 'one turn' secondary is a 12mm-long tapped brass spacer through the centre of the toroid. The effective RF resistance of this spacer is extremely low, and the source resistance is then mainly a function of the ferrite material and the primary winding resistance.

Circuit description

The full circuit of my Q Meter is shown in Fig.5. We require a signal generator with an output of about 0dBm (1mW into 50Ω or 225mV RMS). You can use just about any RF signal generator. There didn't seem to be much point in building the generator into the Q Meter since, if you're building a Q Meter, you likely already have an RF signal generator.

I'm using my *AM/FM DDS Signal Generator* that was described in the May 2023 issue of *PE*.

The generator feeds a sinewave into CON1, which is boosted by op amp IC2a. This is a critical item in the design, as it needs to have a high gain bandwidth (GBW) and slew rate, as well as the capability to drive a low impedance.

Table 1 – frequency versus signal source impedance/spacer

Frequency	Brass	Steel
0.1-1MHz	~0.00Ω	0.02Ω
2MHz	not tested	0.016Ω
5MHz	0.03Ω	0.13Ω
10MHz	0.07Ω	0.20Ω
15MHz	0.09Ω	not tested
20MHz	0.15Ω	0.22Ω
25MHz	0.10Ω	0.17Ω

The Texas Instruments OPA2677 has a GBW of 200MHz, a slew rate of 1800V/μs and can drive a 25Ω load, which gives us enough output voltage swing up to 25MHz.

The toroidal transformer core is a critical part of the design. I tested a Fair-rite 5943000301 core which is readily available from several suppliers. I wound it with 10 turns of 0.3mm-diameter enamelled copper wire. A heavier gauge (up to about 0.4mm) may be slightly better, but there has to be enough room in the centre for the spacer to pass through.

I then calculated the source impedance by measuring the no-load output voltage followed by a 1Ω load. I did this for several frequencies, and the results are shown in Table 1.

Below 1MHz, there was no measurable difference between no load and a 1Ω load, so the source impedance must be well below 0.01Ω. Core losses likely account for the higher source resistance as frequency increases, but the results are quite adequate. Brass spacers are recommended (and will be supplied in kits) due to their superior performance here, at least for the one through the toroid.

The DC output of op amp IC2a is zero or very close to zero, so why do

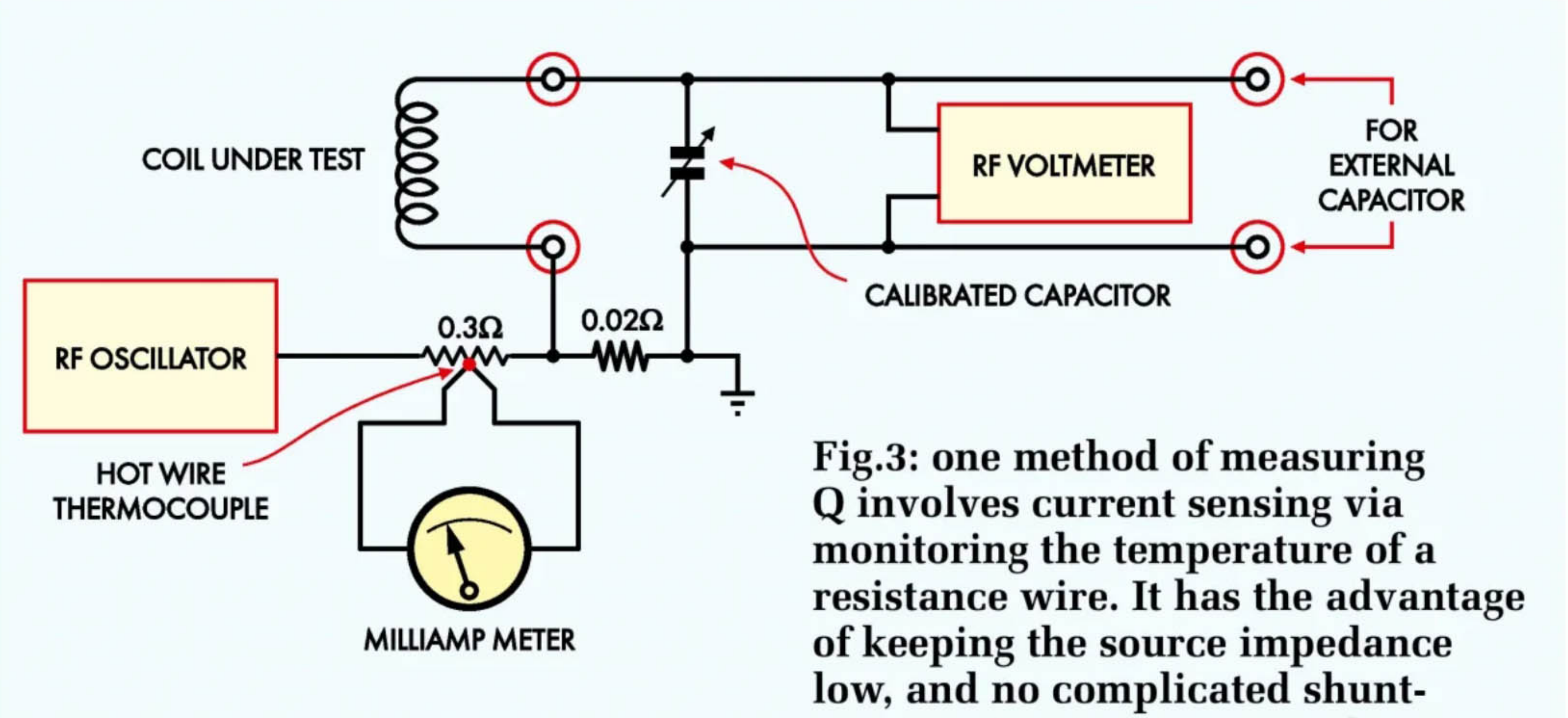


Fig.3: one method of measuring Q involves current sensing via monitoring the temperature of a resistance wire. It has the advantage of keeping the source impedance low, and no complicated shunt-sensing circuitry is required.

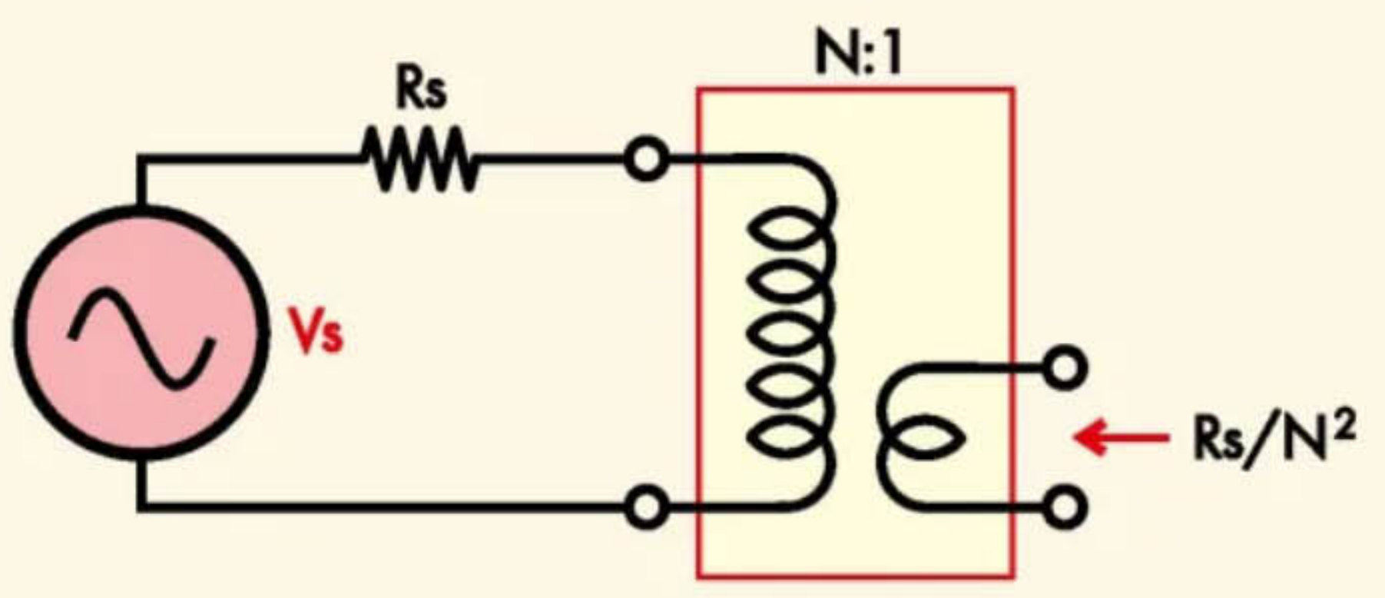


Fig.4: we need an RF signal source with an extremely low (but known) source resistance for our Q Meter. Since that is difficult to achieve by itself, feeding the signal through a low-loss step-down transformer greatly reduces the actual source impedance, as seen by the load.

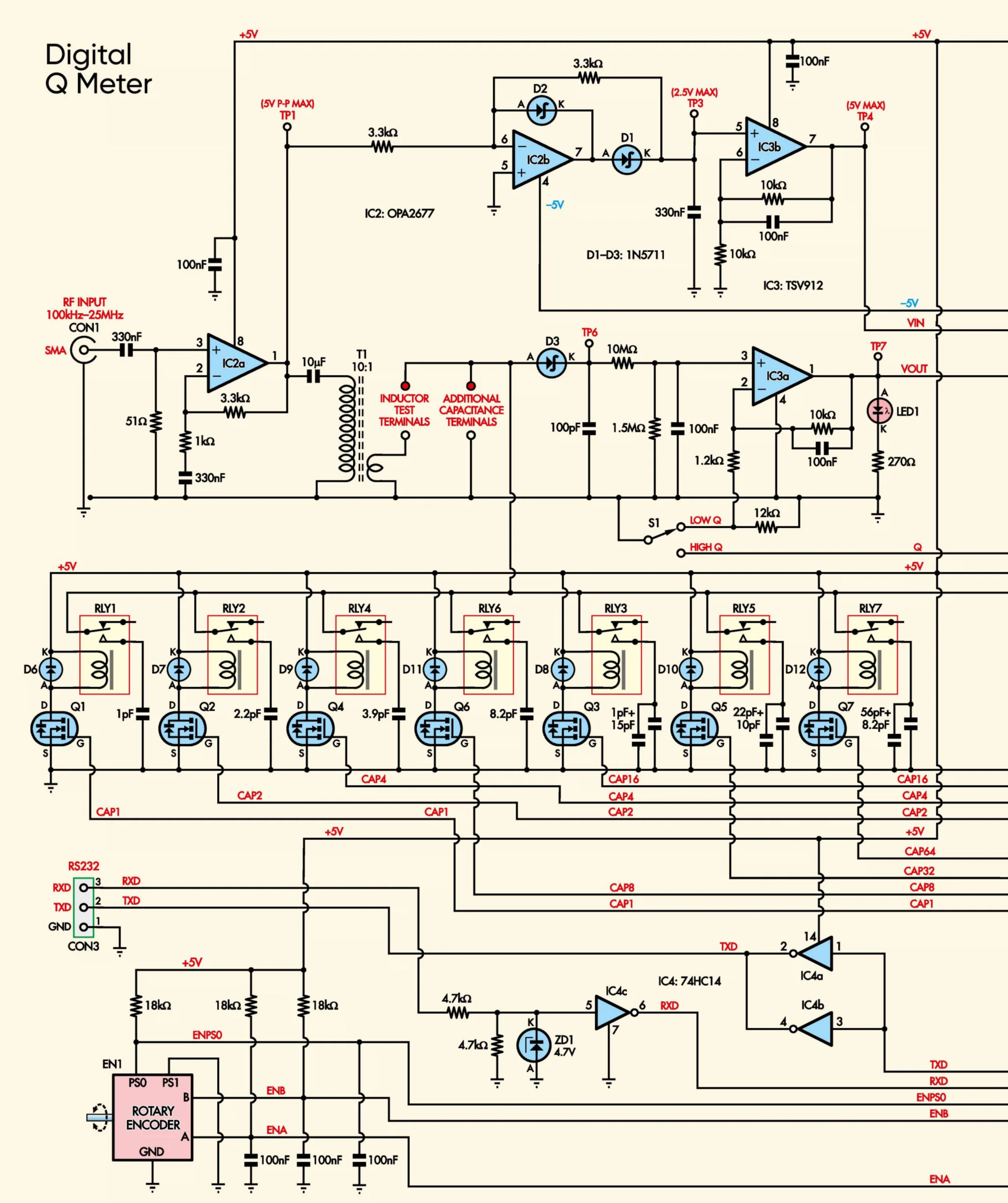
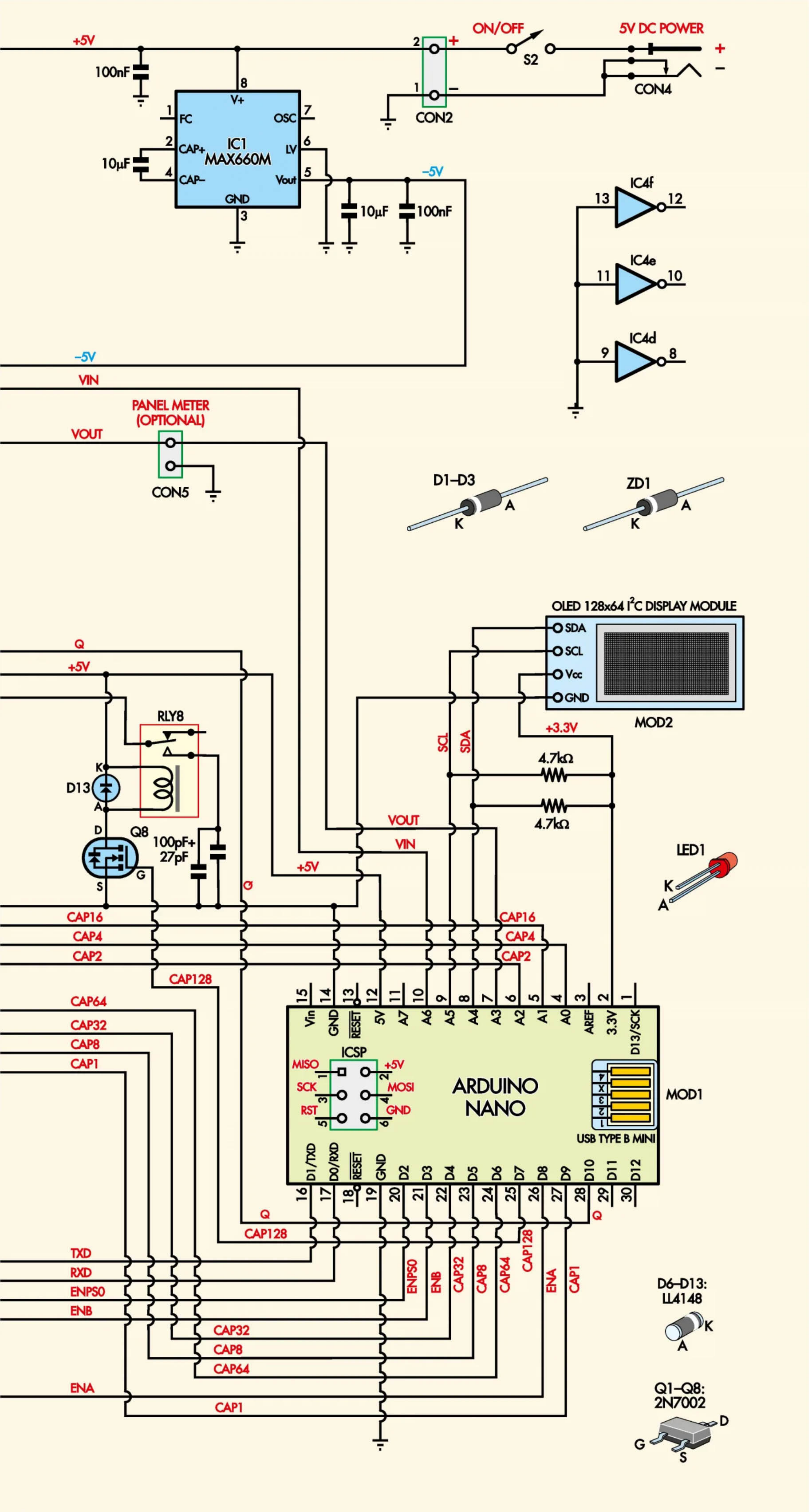

Digital Q Meter
+5V
(5V P-P MAX)
TP1
3.3kΩ
D2
A
K
6
5
IC2b
7
4
D1
−5V
IC2: OPA2677
(2.5V MAX)
TP3
330nF
100nF
8
IC3b
10kΩ
100nF
10kΩ
(5V MAX)
TP4
D1–D3: 1N5711
IC3: TSV912
100nF
RF INPUT
100kHz–25MHz
CON1
SMA
330nF
51Ω
IC2a
1kΩ
330nF
10µF
T1
10:1
INDUCTOR TEST TERMINALS
ADDITIONAL CAPACITANCE TERMINALS
D3
TP6
10MΩ
100pF
1.5MΩ
100nF
IC3a
TP7
VOUT
VIN
LED1
270Ω
1.2kΩ
10kΩ
100nF
S1
LOW Q
HIGH Q
12kΩ
Q
RLY1
RLY2
RLY4
RLY6
RLY3
RLY5
RLY7
D6
D7
D9
D11
D8
D10
D12
Q1
Q2
Q4
Q6
Q3
Q5
Q7
1pF
2.2pF
3.9pF
8.2pF
1pF+ 15pF
22pF+ 10pF
56pF+ 8.2pF
CAP1
CAP2
CAP4
CAP8
CAP16
CAP32
CAP64
RS232
RXD
TXD
GND
CON3
IC4a
IC4b
IC4c
IC4: 74HC14
4.7kΩ
4.7kΩ
ZD1 4.7V
18kΩ
18kΩ
18kΩ
ENPS0
ENB
ENA
EN1
PS0
PS1
ROTARY ENCODER
B
A
GND
100nF
100nF
100nF

Fig.5: eight relays switch capacitors in parallel to vary the resonant circuit capacitance from around 40pF (the stray capacitance) to 295pF. The signal from the RF generator is amplified by op amp IC2a and fed through step-down transformer T1 to the resonant circuit. The input signal level is monitored via precision rectifier IC2b while the output signal is rectified using D3 and amplified by IC3a.

we need a 10µF capacitor in series with the transformer? Since the DC resistance of the primary is a fraction of an ohm, the slightest offset voltage in the op amp output could send a high direct current through the toroidal transformer primary and overload the output. IN this design, that possibility is eliminated with AC coupling.

The tuning capacitor is another essential part. My Meguro MQ-160 Q


+5V
100nF
ON/OFF
S2
5V DC POWER
+
–
CON4
CON2
IC1
MAX660M
V+
FC
OSC
CAP+
LV
CAP–
Vout
GND
10μF
10μF
100nF
–5V
IC4f
IC4e
IC4d
–5V
VIN
PANEL METER
(OPTIONAL)
VOUT
CON5
D1–D3
ZD1
K
A
OLED 128x64 I²C DISPLAY MODULE
SDA
SCL
Vcc
GND
MOD2
+3.3V
4.7kΩ
4.7kΩ
SCL
SDA
Q
+5V
RLY8
D13
Q8
100pF+
27pF
VOUT
VIN
+5V
LED1
CAP16
CAP4
CAP2
CAP128
CAP64
CAP32
CAP8
CAP1
Vin
GND
RESET
5V
A7
A6
A5
A4
A3
A2
A1
A0
AREF
3.3V
D13/SCK
ICSP
MISO
SCK
RST
+5V
MOSI
GND
ARDUINO
NANO
MOD1
USB TYPE B MINI
D1/TXD
D0/RXD
RESET
GND
D2
D3
D4
D5
D6
D7
D8
D9
D10
D11
D12
TXD
RXD
ENPS0
ENB
ENA
ENPS0
ENB
CAP32
CAP8
CAP64
CAP128
ENA
CAP1
D6–D13:
LL4148
Q1–Q8:
2N7002
G
S
D

Meter has a 22-480pF variable capacitor, typical of the tuning capacitors used in valve radios. They are available on sites like eBay, but they do tend to be rather large and can be surprisingly expensive.

The only easy-to-get variable capacitor is the sort with a plastic dielectric for AM radios. But once you get above the broadcast band, they are very lossy, with a poor Q, and entirely unsuitable.

So instead, I designed a 'digital capacitor' with eight relays switching in capacitors with values in a binary sequence of 1, 2, 4, ...128pF. As these are not standard values, some are made up of two capacitors in parallel. For example, 32pF is 22pF in parallel plus 10pF. Combining these allows the capacitance to be adjusted in 1pF steps from 0pF to 255pF.

The measured stray capacitance due to the tracks, relays and so on amounts to 40pF, so the tuning range is 40-295pF. My LC meter shows that it tracks reasonably accurately.

All capacitors are not created equal, so I have used somewhat expensive high-Q RF capacitors, available from element14, Mouser, Digi-Key and other good suppliers. Not all these capacitors have a close tolerance; some are ±2%, which detracts from the accuracy. So it isn't a 'real' variable capacitor but it has the advantage of not needing a calibrated dial and a slow-motion vernier adjustment.

Rather than measuring the very low voltage on the secondary side of the transformer, it is more practical to measure the primary side, and for the Q calculation, divide this by 10. I verified this assumption by checking that the voltage ratio corresponded to the turns ratio within measurement accuracy from 100kHz to 25MHz.

A precision half-wave rectifier is formed using op amp IC2b in the classic configuration. By placing the rectifier diodes in the negative feedback network of the op amp, their forward voltages are effectively divided by the (very high) open-loop gain of the op amp.

On positive excursions of the output pin of IC2b, the 330nF capacitor at TP3 is charged up through diode D1. The extra diode (D2) is needed becuae without it, negative excursions would saturate the op amp and lead to slow recovery, limiting its frequency range. Both diodes are 1N5711 types for fast switching.

The output of IC2b is amplified by IC3b, and the resulting filtered DC voltage at TP4 is about 1.9V.

The secondary voltage of the transformer is typically 200mV peak-to-peak or about 70mV RMS. With a Q of 100, the voltage output at the junction of the inductor and tuning capacitor would be 20V peak-to-peak or 7V RMS.

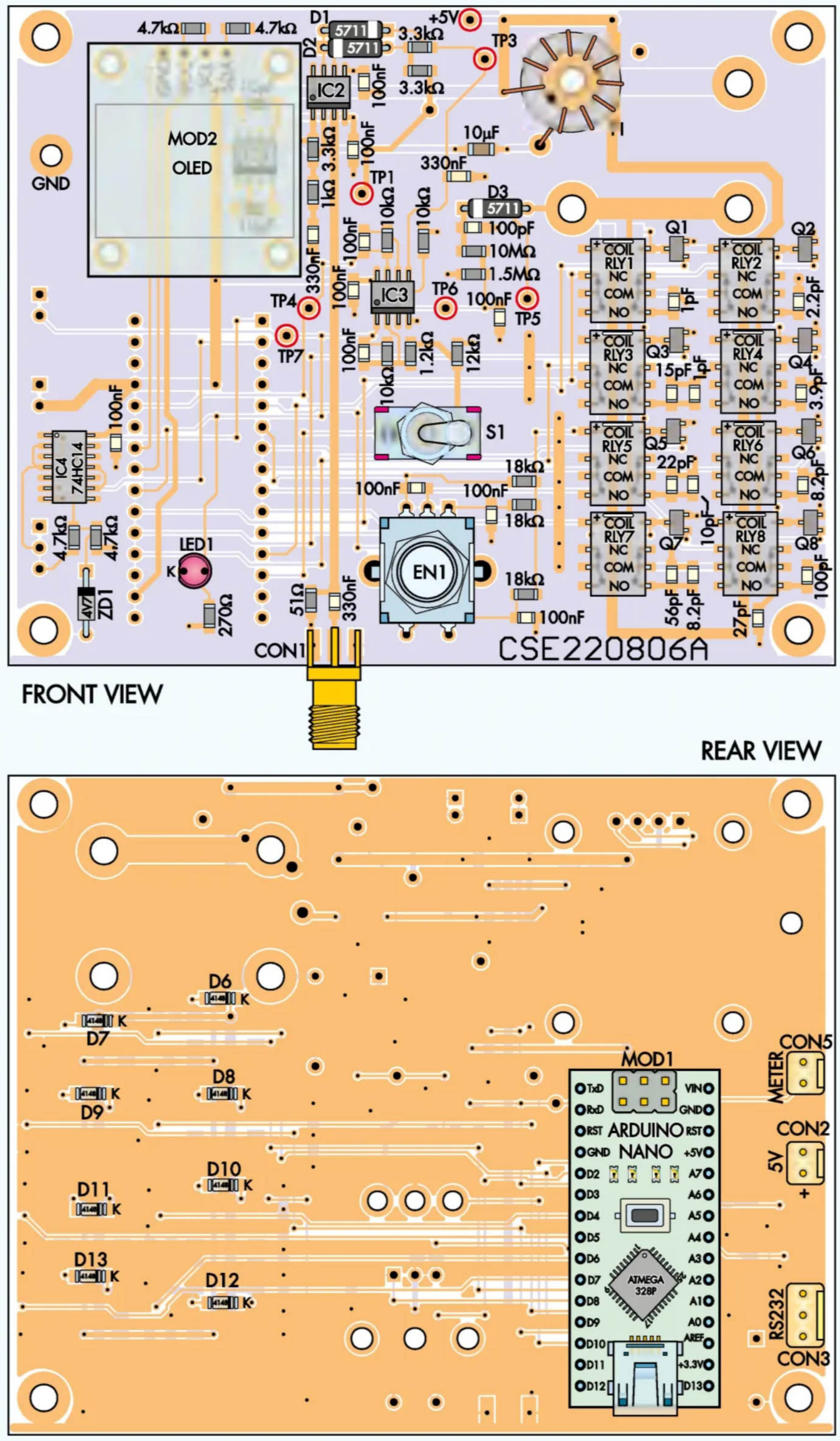

FRONT VIEW
REAR VIEW
MOD2
OLED
GND
IC2
IC3
IC4
74HC14
D1
D2
D3
5711
+5V
TP1
TP2
TP3
TP4
TP5
TP6
TP7
4.7kΩ
3.3kΩ
100nF
10µF
330nF
1kΩ
10kΩ
100pF
10MΩ
1.5MΩ
1.2kΩ
12kΩ
18kΩ
51Ω
270Ω
S1
EN1
LED1
K
ZD1
4V7
CON1
CSE220806A
COIL
NC
COM
NO
RLY1
RLY2
RLY3
RLY4
RLY5
RLY6
RLY7
RLY8
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
1pF
2.2pF
3.9pF
15pF
22pF
8.2pF
10pF
56pF
27pF
D6
D7
D8
D9
D10
D11
D12
D13
MOD1
ARDUINO
NANO
ATMEGA 328P
CON5
METER
CON2
5V
CON3
RS232

Fig.6: the PCB uses mostly SMD components for compactness, although none are particularly small. The orientations of the following components are important: all relays, ICs and diodes, plus the Arduino Nano. ZD1, IC4, CON3 and associated parts form the optional debugging interface.

That is not a suitable voltage to apply to the input of an op amp! So I used schottky diode D3 as a half-wave rectifier feeding a high-impedance (10MΩ/1.5MΩ) voltage divider. The voltage drop in the diode only introduces a small error in the measurement.

The voltage at the junction of this divider is buffered and amplified by IC3a, a TSV912 op amp with an extremely high input impedance – the input bias current is typically 1pA. Switch S1 changes the gain of this op amp for the low and high Q ranges, with the low range giving a gain of 8.3 for Q values of up to 100. On the high range, the gain of this stage drops to 1.7.

Power supply and control

A MAX660 switched capacitor voltage inverter (IC1) provides a nominally –5V supply to the OPA2677 (IC2). This is needed for proper operation of the half-wave precision rectifier (IC2b) since the voltage at its input can swing below ground.

The MAX660 is not a perfect voltage inverter, and with the current drain of the OPA2677, its output is about –3.6V, but that is adequate.

The rest of the circuit operates from a regulated +5V DC fed in externally – for example, using a USB supply.

An Arduino Nano module is used as the controller. This is a readily-available part from many suppliers at a reasonable price. Two analogue inputs are used for measuring the voltages, eight digital outputs switch relays, the two I^{2}C serial lines drive the OLED, and there are inputs for the control rotary encoder and LOW/HIGH switch sensing.

The rotary encoder (EN1) is used to adjust the 'digital capacitor' value; its integral pushbutton switch toggles between steps of 1pF and 10pF.

As usual with my designs, I have added a simplified RS-232 interface using hex schmitt-trigger inverter IC4 to aid code debugging. IC4, ZD1 and the two associated resistors can be left out unless you want to use the debugging interface.

Eight 2N7002 N-channel MOSFETs (Q1-Q8) drive the relay coils, while eight diodes across the relay coils (D6-D13) suppress any switching transients.

The resonant frequency tuning is done by selecting an appropriate frequency from the external signal generator and adjusting the variable capacitance value. Ideally, the peaking should be done with an analogue meter, but I have provided an onboard LED (LED1), the brightness of which depends on the V_{OUT} voltage. It's a simple enough procedure to adjust the capacitance to achieve maximum brightness.

The third line of the OLED also shows the output voltage of IC3a, which can be used to accurately achieve resonance too.

Connector CON5 drives an optional external 0-5V moving-coil meter. You can add such a meter if a larger-than-specified enclosure is used to house the PCB.

The power supply is a standard 5V USB charger. I have not included reverse polarity protection, but an off-board 1A schottky diode (eg, 1N5819) could be added in series if desired.

Construction

The construction uses two PCBs (see Figs.6 and 7). The main one has all the electronics while the other has the screw terminals for the DUT and external capacitor. It is also used as a front panel and has a rectangular cutout for the OLED, holes for the controls and lettering. It is designed to fit in a RITEC 125 × 85 × 55mm enclosure (for example, one sold by Altronics as H0324, but plenty of other vendors will have similar boxes).

The top board/front panel is 98 × 76mm and fits snugly into the recess in the clear lid of the enclosure. This board could be used as a template for accurately drilling the holes in the clear lid. But other enclosures may be used as long as they have the same or slightly greater dimensions as the H0324.

For those wishing to add the 0-5V moving-coil meter, this requires an additional width of 45mm. A suitable 158 × 90 × 60mm enclosure is available from AliExpress suppliers at a reasonable price, but do remeber that delivery can take quite a few weeks.

Most components on the PCB are surface-mount types, but there are no fine-pitch ones, which simplifies construction. Solder the four SOIC chips first, then all the passives, which are mostly M2012/0805-size devices (2.0 × 1.2mm).

The relays take a bit of care to ensure they are square on the board so that it looks neat. On the opposite side of the board are eight 1N4148 equivalent diodes; ensure they are installed with the correct polarity, with the cathode stripes to the side marked ‘K’.

After the SMDs, add the through-hole diodes, which have a 7.6mm (0.3-inch) pitch, then the rotary encoder, switch and LED. Use a 5mm plastic spacer for the LED, so it is flush with the back of the front panel.

Wind ten turns of the specified enamelled copper wire onto the toroidal core, taking care that the turns are equally spaced around the circumference, to the extent possible, and the ends line up with the two pads marked PRIM on the PCB. Carefully attach the toroid so that it is centred on the mounting hole. Attaching the spacer to the board makes that easier.

It may be anchored in place by an insulated wire across the two pads on the opposite side. It is not a shorted turn because only one side of this wire is connected to the ground plane.

I recommend fitting socket strips for mounting the Arduino Nano module as they make replacing a faulty module easy (I have blown up a couple in the past!). The OLED screen also plugs into a 4-pin socket strip and is held in place by two 15mm-long M2 or M2.5 screws through 8mm untapped spacers. Carefully slide off the plastic strip on the four pins of the OLED so that it sits lower.

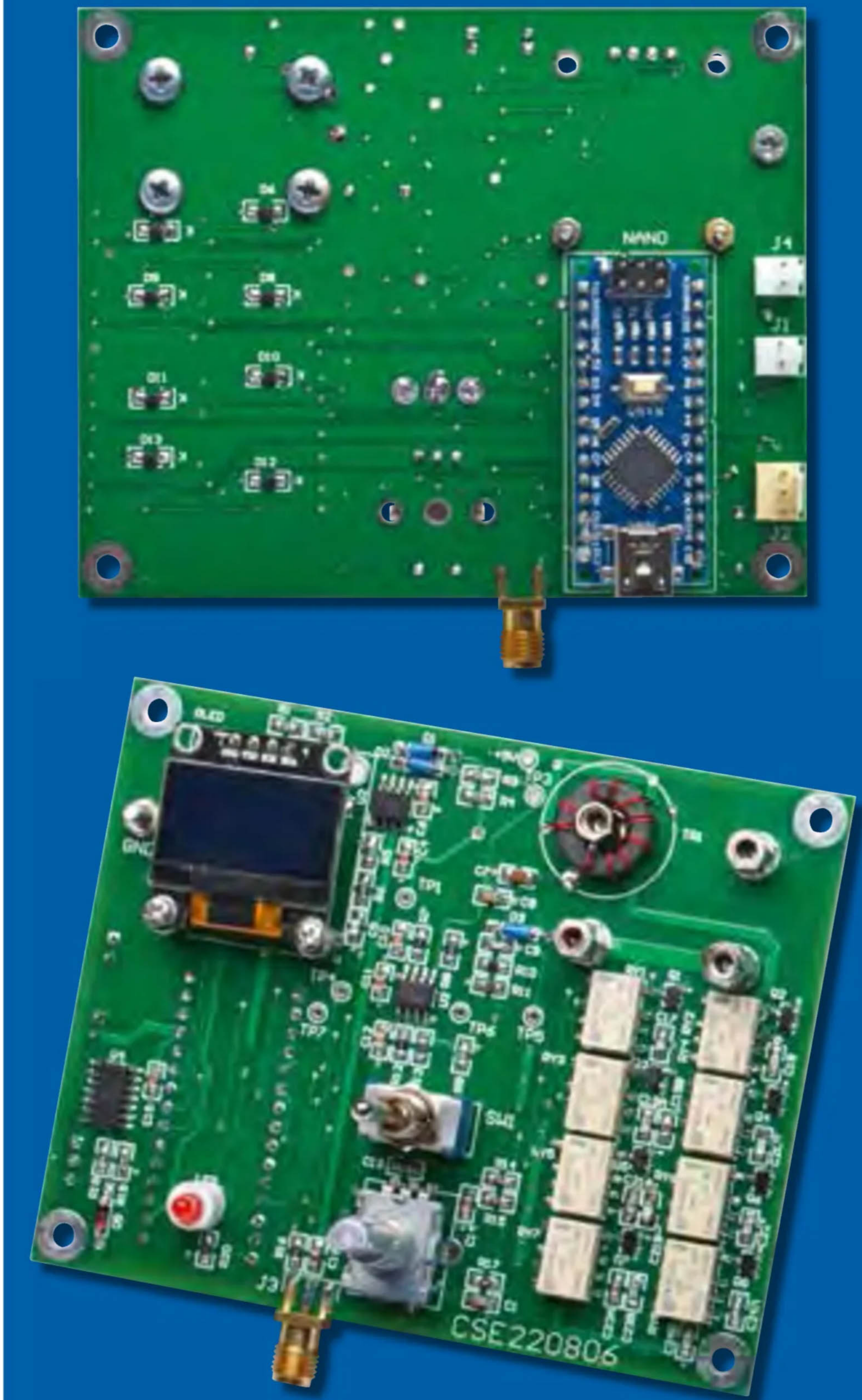
The board must be thoroughly cleaned with board cleaner. There are high impedances throughout the circuit, so be aware that leakage through flux residue would affect its operation – you must remove that residue.

Testing

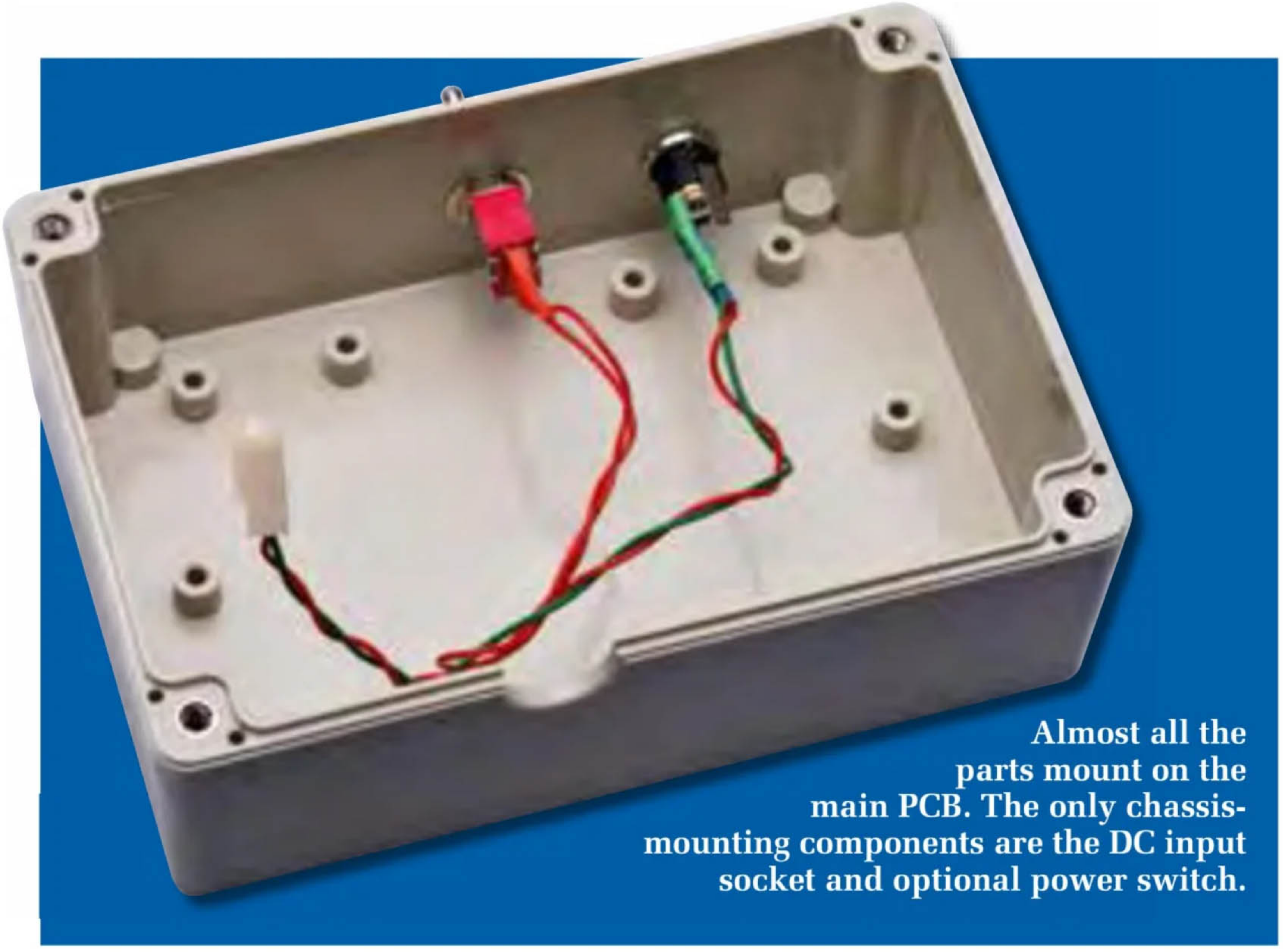
Once the board has been fully assembled, cleaned and inspected, but before it is mounted in the case, attach the four 12mm spacers – but not the front panel board – and connect the 5V supply. The OLED should show an initial message with the firmware version number.

Using a coax cable, feed in a sinewave from a signal generator at about 1MHz. An oscilloscope probe on TP1 should show a clean sinewave, with an output of about 2V peak-to-peak. If the output of the signal generator is too high, you will get flattening on the negative half cycle. In that case, back off the level for a clean sinewave.

Transfer the ‘scope probe to the top of the spacer that passes through the toroid, and the voltage should be one-tenth of that measured at TP1. Measure TP4 using a DC voltmeter;



Only the Arduino Nano, headers and eight diodes are on the underside of the Q Meter PCB. Note how the windings for T1 are spaced evenly around it.



Almost all the parts mount on the main PCB. The only chassis-mounting components are the DC input socket and optional power switch.

you should get a reading of about 2V. Note that these values will depend on the output of the signal generator and could vary.

Rotate the encoder and note that the capacitance value varies by 1pF per detent. Depending on the encoder, it might go backwards. If so, plug a jumper on the Arduino Nano's programming header between pins 4 and 6; that will correct the direction. Push down the knob to change the resolution, and the capacitance should then change by 10pF per detent.

By winding it fully clockwise, the maximum indicated capacitance should show as 295pF on the bottom line of the OLED, with the minimum being 40pF.

Connect a 10µH moulded inductor between the two 'L' spacers, using 3mm machine screws to hold it in place. Adjust the capacitance to 100pF, switch to LOW Q mode and adjust the signal generator frequency to about 5.5MHz. The LED should light up; tune the capacitance for maximum brightness. The second line of the OLED will then most likely display 'TOO HIGH'.

Switch to HIGH Q mode, which will dim the LED, and re-tune for maximum brightness. Depending on the inductor, a typical Q reading will be about 120. If you get a sensible reading and can peak the LED brightness by varying the capacitance, your *Q Meter* is most likely functioning correctly, so it can be finished.

The front panel is mounted on the front of the case, and the main PCB may now be attached by the four spacers using four 8mm M3 machine screws. To improve the appearance, use black screws or spray the heads flat black.

Note that the binding posts must make electrical contact with the bare pads on the front panel PCB; attach them with the supplied nuts and make sure they are making good contact. The tapped spacers connecting the two boards must also make good electrical contact at both ends.

Using it

The operation of the *Q meter* requires some initial measurements and calculations. We need to know at least the approximate inductance of the DUT. I use my *LC Meter* for measuring this, as described in the November 2023 issue of *PE*.

With the inductance known or guessed, we need to determine the frequency at which to measure the Q. That will be influenced by the inductor value and the frequency at which you want to use the inductor. Once you've selected a frequency, plug the values into the formula:

$$C = 25330 / (2 \times f \times L)$$

Where C is in pF, f is in MHz and L is in µH.

If you get a value of C below 40pF, select a lower frequency and redo the calculation; if you get a value above 295pF, choose a higher frequency. Repeat until your calculated capacitance is in the range of 40-295pF.

Set the capacitance to that value and adjust the frequency from the signal generator, or the capacitance, for resonance. The resulting Q will be shown on the second line of the OLED. If the switch is set to LOW and the Q exceeds 100, the second line will show 'TOO HIGH'. In that case, switch to the HIGH position.

I find that it is better to start with the switch set to LOW since it is then easier to figure out if you are close to resonance.

The 'C' terminals allow a capacitor to be placed in parallel with the internal capacitance in case you can't achieve resonance at a sensible frequency with the available range. So that it doesn't detract from the Q, make sure you use a high-quality RF capacitor.

Accuracy

This meter is certainly not as accurate as the HP4342-A meter mentioned earlier. Without any standard coils of known Q, it is difficult to determine the true accuracy.

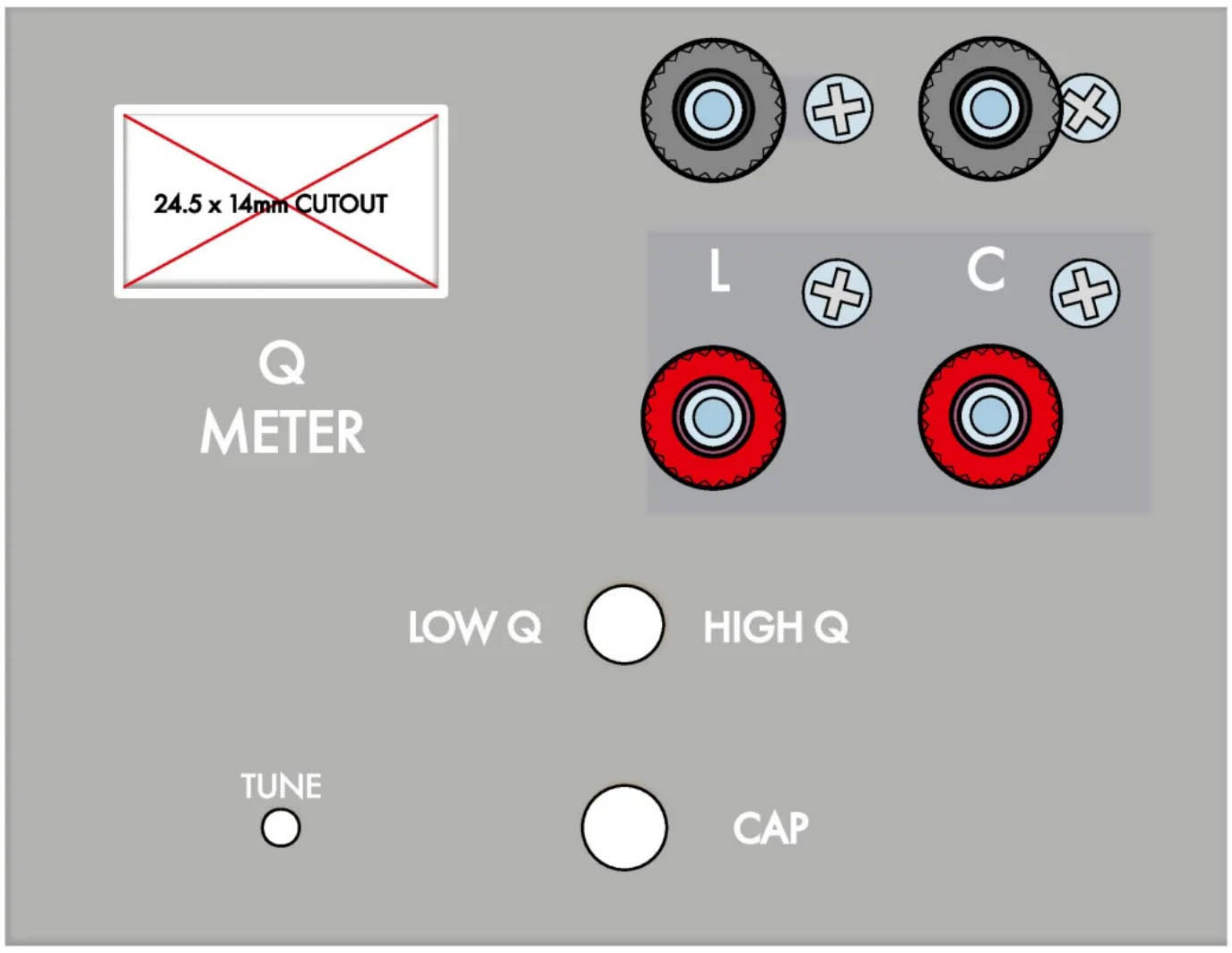


Fig.7: the circuitry on the front panel PCB just consists of one large track connecting the two red terminals and smaller tracks connecting the upper screws to their adjacent binding posts. It also has holes and labels for the controls and screen.

Parts List – Q Meter

1 RF signal generator (see *PE*, May 2023;
1 RITEC 125 × 85 × 55mm plastic enclosure **[Altronics H0324]**
1 double-sided PCB coded CSE220701, 99 × 79mm
1 double-sided PCB coded CSE220704, 98 × 76mm, black solder mask (both PCBs available from the *PE PCB Service*)
1 chassis-mounting SPST toggle switch with solder tabs (S1)
1 0-5V analogue meter (**optional**)
1 Arduino Nano (MOD1)
1 0.96in OLED display module with I^2C interface and SSD1306 controller (MOD2)
8 G6K-2F-Y SPDT SMD relays (RLY1-RLY8)
1 rotary encoder with integral pushbutton (EN1)
1 knob to suit EN1
1 Fair-rite 5943000301 ferrite toroidal core, 12mm OD, 8mm ID, 5mm thick (T1)
1 30cm length of 0.25-0.4mm diameter enamelled copper wire (T1)
1 SMA edge connector (CON1)
2 2-pin polarised headers (CON2, CON5)
1 3-pin polarised header (CON3) ♦
1 2.1mm or 2.5mm inner diameter chassis-mount jack socket (CON4)
2 red 4mm chassis-mounting banana socket/binding posts
2 black 4mm chassis-mounting banana socket/binding posts
4 M3 × 12mm brass spacers
4 M3 × 5mm nickel-plated panhead machine screws
4 M3 × 8mm nickel-plated panhead machine screws
2 M2 × 16mm machine screws and nuts
2 8mm-long untapped plastic spacers
1 5mm-long plastic LED spacer
1 20cm length of light-duty figure-8 hookup wire

Semiconductors
1 MAX660M switched capacitor voltage inverter, SOIC-8 (IC1)
1 OPA2677 dual ultra-high GBW op amp, SOIC-8 (IC2)
1 TSV912 dual high input impedance op amp, SOIC-8 (IC3)
1 74HC14 hex inverter, SOIC-14 (IC4) ♦
1 3mm red diffused lens LED (LED1)
8 2N7002 MOSFETs, SOT-23 (Q1-Q8)
1 4.7V 400mW axial zener diode (ZD1) ♦
3 1N5711 axial schottky diodes (D1-D3)
8 LL4148 75V 200mA diodes, SOD-80 (D6-D13)

Capacitors *(all SMD M2012/0805 X5R or X7R)*
3 10µF 16V
3 330nF 50V
10 100nF 50V

RF capacitors *(all ±2% 200V SMD M2012 or M1608 C0G/NP0 unless noted)*
2 100pF 50V
1 56pF
1 27pF
1 22pF
1 15pF
1 10pF
2 8.2pF
1 3.9pF ±0.1pF
1 2.2pF ±0.1pF
2 1.0pF ±0.1pF

Resistors *(all SMD M2012/0805 1%)*
1 10MΩ
1 1.5MΩ
1 12kΩ
3 18kΩ
3 10kΩ
4 4.7kΩ
3 3.3kΩ
1 1.2kΩ
1 1kΩ
1 270Ω
1 51Ω

♦ *optional components only required for debugging interface*

But even the HP4342-A does not claim any better accuracy than ±7% for frequencies below 30MHz, and considerably worse for higher frequencies – see the PDF manual at: **https://bit.ly/pe-jan24-hpq**

I compared my results with the Meguro meter, but being over 50 years old, it is hardly to be trusted! Still, measurements of the same coil with the Meguro and my meter were generally within 10%.

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For more information or software download please visit
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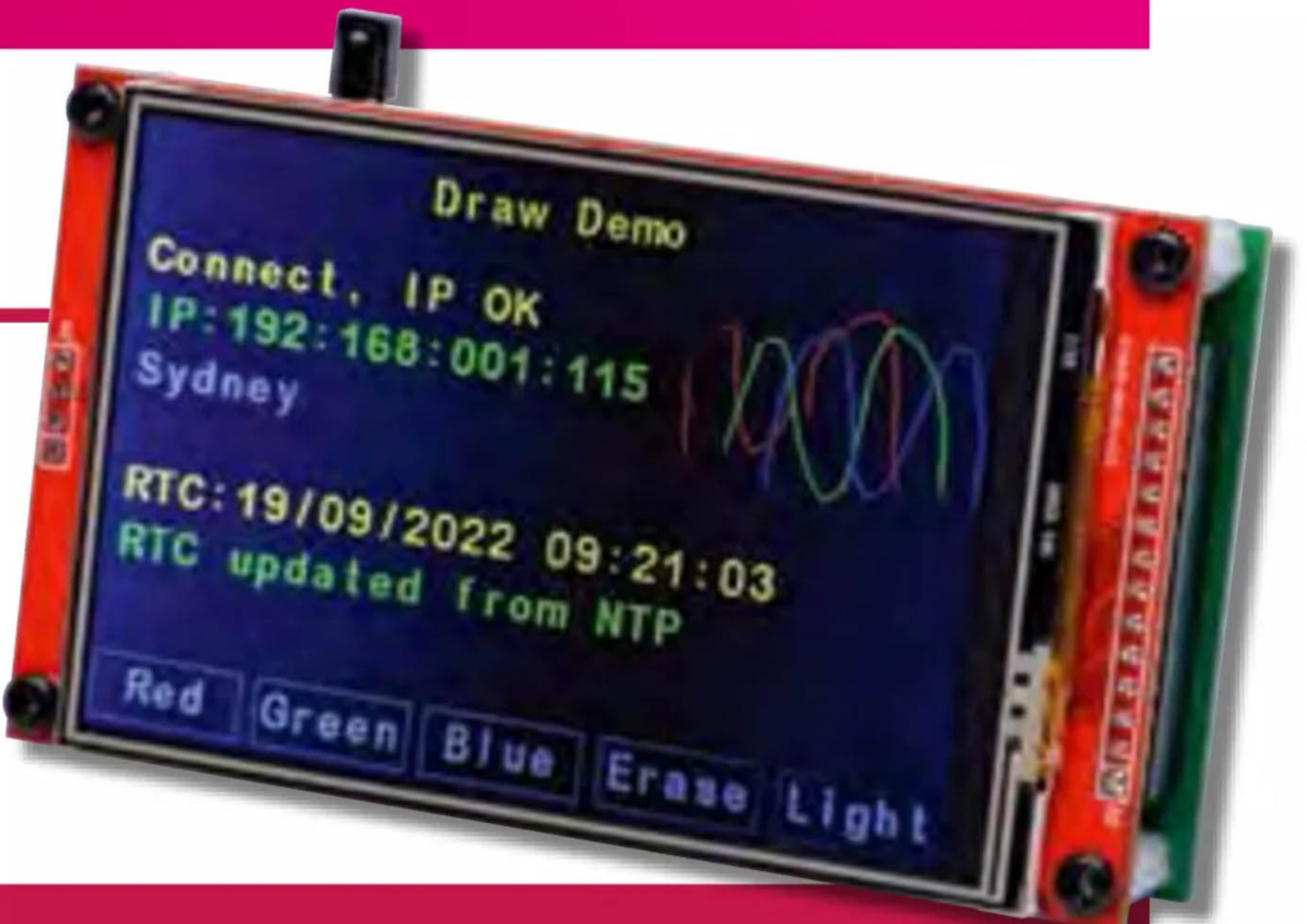
PoKeys
Connect, Control
- USB
- Ethernet
- Web server
- Modbus
- CNC (Mach3/4)
- IO
- PWM
- Encoders
- LCD
- Analog inputs
- Compact PLC
Stepper motor drivers
Drive
- up to 256 microsteps
- 50 V / 6 A
- USB configuration
- Isolated
- up to 32 microsteps
- 30 V / 2.5 A
PoScope Mega1+
PoScope Mega50
Measure
- up to 50MS/s
- resolution up to 12bit
- Lowest power consumption
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator

Raspberry Pi Pico W BackPack

Our Raspberry Pi Pico BackPack from March 2023 has a powerful dual-core 32-bit processor, 480 × 320 pixel colour touchscreen, onboard real-time clock, SD card socket, stereo audio output and infrared receiver. Now, for about £5 more, it has Wi-Fi too!


Draw Demo
Connect, IP OK
IP:192:168:001:115
Sydney

RTC:19/09/2022 09:21:03
RTC updated from NTP

Project by Tim Blythman

Raspberry Pi is a trademark of the Raspberry Pi Foundation

Microcontrollers have become so easy to use, cheap and accessible for hobbyists, while chips like the ESP8266 have made it simple to use Wi-Fi.

The Raspberry Pi Foundation's Pico W is an inexpensive, well-documented 32-bit microcontroller board with Wi-Fi that is well-suited to being used with the LCD BackPack.

Examining the Pico W, we found that it was mostly interchangeable with the Pico but with added Wi-Fi support. So it was only natural to update the *Pico BackPack* to include Wi-Fi support using the Pico W. As it turns out, that was not hard to do.

From launch, the Pico supported the MicroPython and C languages (using the Raspberry Pi Foundation's C software development kit). Arduino support in the form of the Arduino Pico board profile came soon after.

The Raspberry Pi Foundation has made many inexpensive single-board computers and microcontroller boards available to the masses, even during the recent electronics component and device shortages.

Features and Specifications

- Includes a 3.5-inch LCD touch panel and a dual-core microcontroller with Wi-Fi.
- Also includes all the features of the original Pico BackPack.
- We provide software demos and examples for the Arduino IDE, C SDK and MicroPython.
- Our provided sample code demonstrates practical uses of HTTP, UDP and NTP.

The Pi Pico series are simple but well-thought-out boards, and are attractively priced for what they offer.

BackPack hardware

We considered whether it was worthwhile to update the *Pico BackPack* PCB to complement the Pico W, but ultimately, we decided not to make any significant changes.

The thing is, the *Pico BackPack* crams a lot of features into a small area corresponding to the size of the matching LCD touch panel.

To add any features would likely mean removing some of the existing features, which we didn't want to do. The *Pico BackPack* has a row of I/O pins to make external connections, so it's easy enough to connect different hardware if necessary.

Thankfully, we'd already established that the Pico W didn't 'break' any existing functionality of the *Pico BackPack*. So the *BackPack* PCB remains the same for the Pico W, although we will recommend a minor assembly variation to enhance the Wi-Fi capability.

The Pico W BackPack

The only substantial difference between the *Pico BackPack* and the *Pico W BackPack* is the replacement of the Pico module with a Pico W. All the pins on the Pico W are labelled the same as those on the Pico, so none of the signals or I/O pin breakouts need to change.

Remember that both the *BackPack* PCB and LCD touch panel have large solid copper areas that could impede Wi-Fi signal propagation.

Therefore, we recommend that the Pico W is mounted slightly away from the *BackPack* PCB to provide better clearance for its onboard Wi-Fi antenna. We used header strips to provide this spacing.

You could also use low-profile socket headers and short pin headers if you wish to make the Pico W pluggable. We tried this and found it worked well, although it was fiddly to assemble.

Circuit details

Fig.1 shows the circuit diagram for the *Pico W BackPack*. It is identical to the original *Pico BackPack*, with the Pico replaced by a Pico W.

IRRX1 at top left allows the Pico W to receive IR signals on its GP22 digital input. The LCD touch panel connects to power and the SPI bus at the top, as does the microSD card socket at upper right.

The two transistors on the right control the power to the LED backlight on the LCD touch panel. Below this, a DS3231 real-time clock and calendar IC connect to the I^{2}C bus.

Finally, the components at the bottom, including the op amps, can deliver line-level audio at CON3. They connect to pins on the Pico W that generate pulse-width modulated (PWM) signals to provide synthesised analogue voltages.

For more details and specifics about how the various features work on the *Pico BackPack* PCB, refer to the March 2023 article which discusses software to interface to the BackPack hardware.

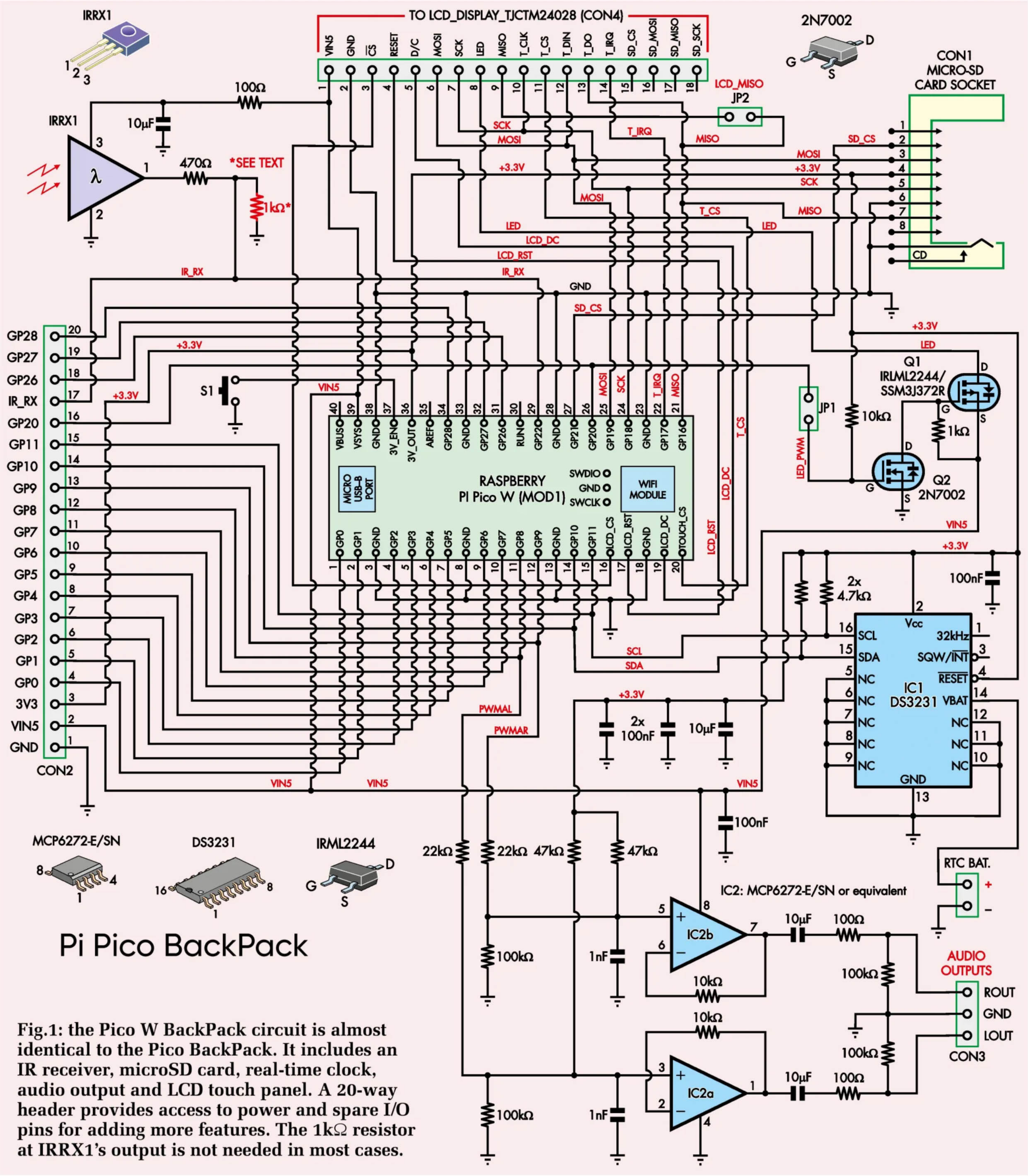

IRRX1
TO LCD_DISPLAY_TJCTM24028 (CON4)
VIN5
GND
CS
RESET
D/C
MOSI
SCK
LED
MISO
T_CLK
T_CS
T_DIN
T_DO
T_IRQ
SD_CS
SD_MOSI
SD_MISO
SD_SCK
2N7002
CON1 MICRO-SD CARD SOCKET
LCD_MISO
JP2
100Ω
10μF
470Ω
*SEE TEXT
1kΩ*
IR_RX
GND
SD_CS
+3.3V
S1
JP1
10kΩ
Q1 IRLML2244/ SSM3J372R
1kΩ
Q2 2N7002
LED_PWM
RASPBERRY PI Pico W (MOD1)
MICRO USB-B PORT
WIFI MODULE
SWDIO
SWCLK
GP28
GP27
GP26
IR_RX
GP20
GP11
GP10
GP9
GP8
GP7
GP6
GP5
GP4
GP3
GP2
GP1
GP0
3V3
VIN5
GND
CON2
2x 4.7kΩ
100nF
IC1 DS3231
SCL
SDA
Vcc
32kHz
SQW/INT
RESET
VBAT
NC
2x 100nF
10μF
PWMAL
PWMAR
22kΩ
47kΩ
100kΩ
1nF
IC2: MCP6272-E/SN or equivalent
IC2b
IC2a
RTC BAT.
AUDIO OUTPUTS
ROUT
LOUT
CON3
MCP6272-E/SN
DS3231
IRML2244
Pi Pico BackPack

Fig.1: the Pico W BackPack circuit is almost identical to the Pico BackPack. It includes an IR receiver, microSD card, real-time clock, audio output and LCD touch panel. A 20-way header provides access to power and spare I/O pins for adding more features. The 1kΩ resistor at IRRX1's output is not needed in most cases.

Construction

While that March 2023 article has more detail on assembling the PCB and fitting it to the LCD touch panel, experienced constructors should have no trouble using the overlay in Fig.2 to assemble the PCB. If you refer to that earlier article, the PCB construction is no different until you get to the Pico W module.

Most IR receivers will not need the 1kΩ resistor; in fact, it will interfere with their weak internal pullup. Hence, it has been omitted from the overlay and is not seen in our photos. Don't forget the cell holder on the reverse of the PCB if you are fitting the real-time clock IC.

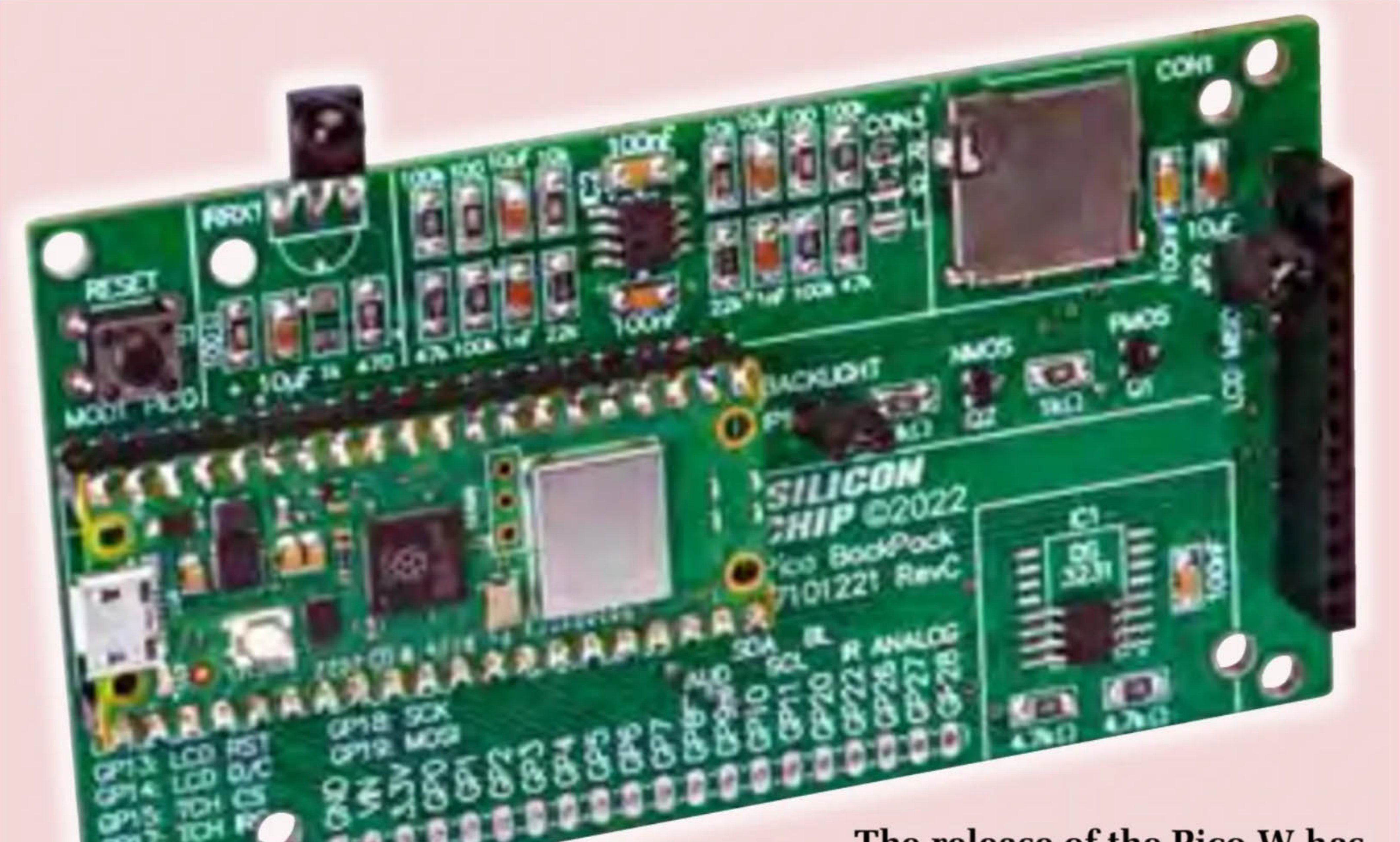
Lines separate the various sections of the board on the silkscreen. That helps you to omit some components if you wish to reclaim some I/O pins by not using those features.

As we mentioned earlier, the Pico W should be spaced away from the main BackPack PCB and also kept clear of the LCD above. Thus, we have added two 20-way pin header strips to the parts list. Solder these to the *BackPack* PCB, with the plastic carrier sitting above. Then solder the Pico W to the top of the pin headers. The plastic carrier separates the Pico W from the *BackPack* PCB.

Our photos show how the Pico W is spaced above the *BackPack* PCB by a small distance.

The other option requires low-profile (5mm) header sockets too. Altronics Cat P5398 (for example) can be used but you will need two lengths, cutting them down to 20 pins each.

The fiddly part is fitting the pin headers to the Pico W, as this requires removing the metal pins from their plastic carrier to minimise the height. Although



The release of the Pico W has allowed us to update the Pico BackPack with Wi-Fi. It's a powerful combination that we think will be the basis of some diverse and interesting projects. We're providing several practical Wi-Fi demos to make it easy to pick up and use.

the plastic carrier is only 2.5mm high, it's enough to cause the Pico W to foul the LCD, so it must be removed.

After pulling the pins out of the plastic carrier, insert them individually into the socket header entries. You can then place Pico W over the pins and solder them to it. Depending on the length of the pins, they might also need to be trimmed so that the pins do not foul the LCD screen.

The only advantage of that more fiddly approach is that the Pico W is removable. We figure it's inexpensive enough that you are better off saving the effort and just soldering it.

Software with Wi-Fi support

Of course, we need some sample code that uses Wi-Fi to show off the Pico W's new feature. Since PicoMite BASIC will not support the Pico W's Wi-Fi, our software samples do not include PicoMite BASIC.

Existing PicoMite BASIC programs should work fine on the Pico W, with the minor exception that the Pico W's onboard LED is driven differently, so it can't be controlled as it would be on a Pico.

We have updated the Arduino, C SDK and MicroPython examples to add Wi-Fi features. As we noted in our review of the Pico W, a document called 'Connecting to the Internet with Raspberry Pi Pico W' explains how to do this with the C SDK and MicroPython. But that guide is quite basic; our sample code does much more.

Since the updated demos are based on the earlier versions we made for the original *Pico BackPack*, we recommend reading the original *Pico BackPack* article for information on the original features.

One of the great features of the Pico and the Pico W is the bootloader which implements a virtual flash drive, allowing software to be uploaded by simply copying a file to the virtual drive.

The bootloader is in mask ROM in the RP2040 microcontroller that runs the Pico and Pico W. This makes it practically impossible to 'brick' the Pico or Pico W, as the bootloader cannot be overwritten.

Bootloader mode is entered by holding down the BOOTSEL button on the Pico or Pico W while powering up or resetting the chip. Since the *BackPack* provides a reset button, you can start the bootloader by pressing and holding BOOTSEL while pressing S1 on the *BackPack*.

Software images for the Pico and Pico W use the UF2 file type, which is a binary format, unlike the text-based HEX files used for other chips like PIC microcontrollers. If you are simply interested in seeing what the *Pico W BackPack* is capable of doing, all you need to do is copy the respective UF2 file to it after putting the Pico W into bootloader mode.

We'll go into a bit more detail about the workings of the software later in this article.

To simplify entering the Wi-Fi credentials, you can set them using the virtual serial port. You will need a serial terminal program, such as TeraTerm, minicom or the Arduino Serial Monitor, to communicate with the Pico W.

You might notice that the demo .uf2 files are larger than the Pico examples due to the extra libraries needed to communicate with the Wi-Fi chip. The Wi-Fi chip also needs a 300kB binary 'blob' to work, which is bundled into the firmware images.

Arduino coding

The team that created the Arduino-Pico port for the Arduino IDE has done a good job of aligning the Pico W's Wi-Fi API (application programming interface) to that used by other Wi-Fi boards, such as those based on the ESP8266 and ESP32 processors. Indeed, it is based heavily on that of the ESP8266.

You might remember the *D1 Mini BackPack* from the October 2021 issue of *PE*. It uses an ESP8266-based D1 Mini module to drive an LCD touch panel and has many features in common with the *Pico W BackPack*.

We're using version 2.5.2 of the Arduino-Pico board profile, although versions as old as 2.30 should support the Pico W. You can find more information about the board profile at: **https://github.com/earlephilhower/arduino-pico**

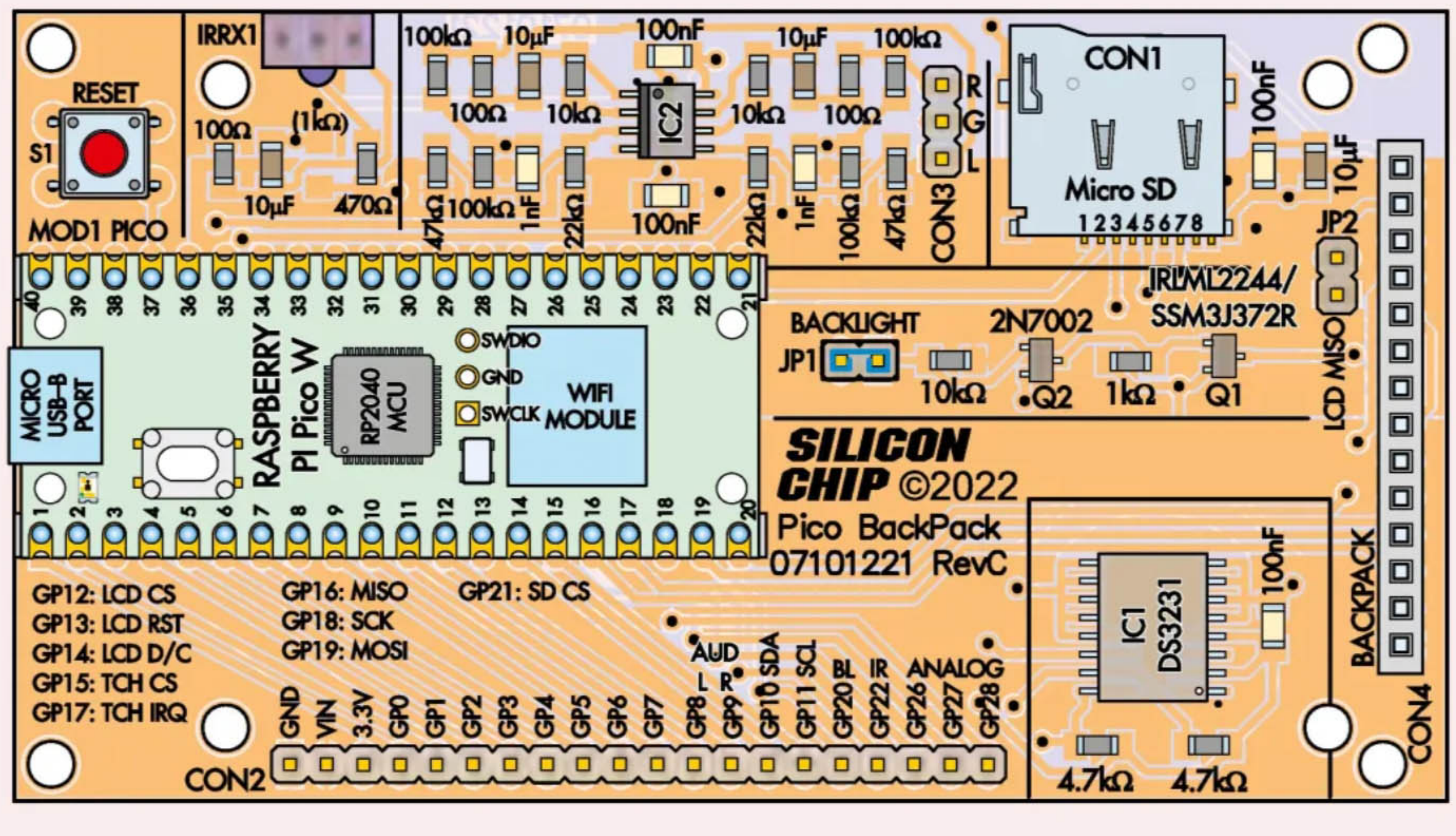

IRRX1
RESET
S1
MOD1 PICO
100Ω
(1kΩ)
10µF
470Ω
100kΩ
10µF
100Ω
10kΩ
100nF
IC2
10µF
100kΩ
10kΩ
100Ω
47kΩ
100kΩ
1nF
22kΩ
100nF
22kΩ
1nF
100kΩ
47kΩ
CON3
R
G
L
CON1
Micro SD
12345678
100nF
10µF
JP2
IRLML2244/
SSM3J372R
BACKLIGHT
2N7002
JP1
10kΩ
Q2
1kΩ
Q1
LCD MISO
MICRO USB-B PORT
RASPBERRY PI Pico W
RP2040 MCU
SWDIO
GND
SWCLK
WIFI MODULE
SILICON CHIP ©2022
Pico BackPack
07101221 RevC
IC1
DS3231
100nF
BACKPACK
GP12: LCD CS
GP13: LCD RST
GP14: LCD D/C
GP15: TCH CS
GP17: TCH IRQ
GP16: MISO
GP18: SCK
GP19: MOSI
GP21: SD CS
AUD
L R
BL
IR
ANALOG
GND
VIN
3.3V
GP0
GP1
GP2
GP3
GP4
GP5
GP6
GP7
GP8
GP9
GP10 SDA
GP11 SCL
GP20
GP22
GP26
GP27
GP28
CON2
4.7kΩ
4.7kΩ
CON4

Fig.2: the lines on the overlay delineate the components that provide the different features of the Pico W BackPack. There is also a cell holder on the rear of the PCB, used by the real-time clock IC to keep time when power is not otherwise available. The Pico W is spaced above the main PCB to improve the performance of its Wi-Fi antenna.

As well as adding Wi-Fi support, we've updated the Arduino sample code to include an infrared receiver decoding library. In our original *Pico BackPack* article, we mentioned that we expected the IRRemote library to be ported to the Pico (and Pico W), which has now happened.

You can find that library online at **https://github.com/Arduino-Irremote/Arduino-Irremote** or it can be installed by searching for 'irremote' in the Arduino Library Manager. We have also included a copy of the version we've used in the software bundle.

Screen 1 shows the *BackPack* running our updated Arduino Pico W sample. We have added some text to the LCD panel to show the status of the Wi-Fi hardware.

Setting up the Wi-Fi

Since using the Pico W in a meaningful way requires that it connect to a Wi-Fi network, we have added a configuration menu on the virtual serial port. We did it that way, rather than using the touchscreen, because it's easier to enter Wi-Fi credentials via a computer rather than an on-screen keyboard.

Screen 2 shows the menu that is presented over the serial port by the Arduino software. Items are selected by typing the number and pressing the Enter key. Items 2 and 3 will prompt for the SSID name and password, also followed by Enter.

This demo can scan for Wi-Fi networks and connect by name and password. It can also connect to a website over HTTP to retrieve data from the internet. In this case, we have used **ip-api.com** to get some location text to display, along with a timezone offset for that location.

This isn't perfect and would probably be fooled by a VPN (virtual private network), but it will usually give the correct timezone. We think it is a simple and effective way of demonstrating the use of HTTP on the Pico W.

We also use NTP (network time protocol) to provide the current time in UTC, adjusted by the timezone offset to provide accurate local time. This can then be saved to the RTC IC on the BackPack.

To do all this, you would use menu items 2, 3 and 4 to connect to a Wi-Fi network, followed by 8 to get the offset and 7 to set the RTC. You can set the offset manually using item 6 if item 8 does not work.

The IRRemote library is also used to capture and decode IR signals, as displayed in the line beginning 'NEC' in Screen 1. This indicates that an NEC code was last received and shows that code.

Parts List – Pico W BackPack

1 double-sided PCB coded 07101221, 99 x 55mm (from *PE PCB Service*)
1 Raspberry Pi Pico W Module (MOD1) **[Altronics, Core, Digi-Key, Little Bird]**
1 3.5in LCD touchscreen **[SILICON CHIP Shop Cat SC5062]**
1 14-pin, 2.54mm pitch socket header (for LCD panel)
3 20-pin, 2.54mm pitch pin header (CON2 & to mount Pico W)
2 20-pin low-profile (5mm tall) 2.54mm pitch socket headers (**optional**)
2 2-pin, 2.54mm pitch pin headers with jumper shunts (JP1, JP2)
1 6mm x 6mm tactile switch (S1)
8 M3 x 6mm panhead machine screws
4 M3 x 12mm tapped spacers

Semiconductors
1 IRLML2244TRPBF/SSM3J372R P-channel MOSFET, SOT-23 (Q1)
1 2N7002 N-channel MOSFET, SOT-23 (Q2)

Resistors *(all M3216/1206, 1%, ⅛W)*
1 10kΩ
1 1kΩ

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Optional Components

SD card
1 SMD microSD card socket (CON1) **[Altronics P5717]**
1 10µF 10V X7R SMD ceramic capacitor, M3216/1206 size
1 100nF 10V X7R SMD ceramic capacitor, M3216/1206 size

Real time clock/calendar
1 surface-mounting CR2032 cell holder (BAT1) **[BAT-HLD-001]**
1 DS3231 or DS3231M in SOIC-16 (wide) or SOIC-8 package (IC1)
1 100nF 10V X7R SMD ceramic capacitor, M3216/1206 size
2 4.7kΩ 1% ⅛W M3216/1206 size

IR receiver
1 3-pin infrared receiver (IRRX1) **[Jaycar ZD1952]**
1 10µF 10V X5R SMD ceramic capacitor, M3216/1206 size
1 1kΩ 1% ⅛W resistor M3216/1206 size (see text)
1 470Ω 1% ⅛W resistor M3216/1206 size
1 100Ω 1% ⅛W resistor M3216/1206 size

Stereo audio
1 MCP6272(T)-E/SN, MCP6002(T)-I/SN or -E/SN dual op amp, SOIC-8 (IC2)
1 3-pin, 2.54mm pitch pin header (CON3)
2 1nF 25V X7R SMD ceramic capacitors, M3216/1206 size
2 100nF 10V X7R SMD ceramic capacitors, M3216/1206 size
2 10uF 10V X5R SMD ceramic capacitors, M3216/1206 size
4 100kΩ 1% ⅛W resistor M3216/1206 size
2 47kΩ 1% ⅛W resistor M3216/1206 size
2 22kΩ 1% ⅛W resistor M3216/1206 size
2 10kΩ 1% ⅛W resistor M3216/1206 size
2 100Ω 1% ⅛W resistor M3216/1206 size

Code differences

The Arduino code for the updated *Pico W BackPack* differs from the earlier *Pico BackPack* example only in the main sketch file, plus the requirement to have the IRRemote library installed. It uses other library files that are part of the Arduino-Pico board profile, including those needed for Wi-Fi.

Those who have worked with modules based on the ESP8266 or ESP32 will be familiar with how Wi-Fi works under the Arduino IDE; the Pico W is similar. Three library 'includes' are used to implement the Wi-Fi features:

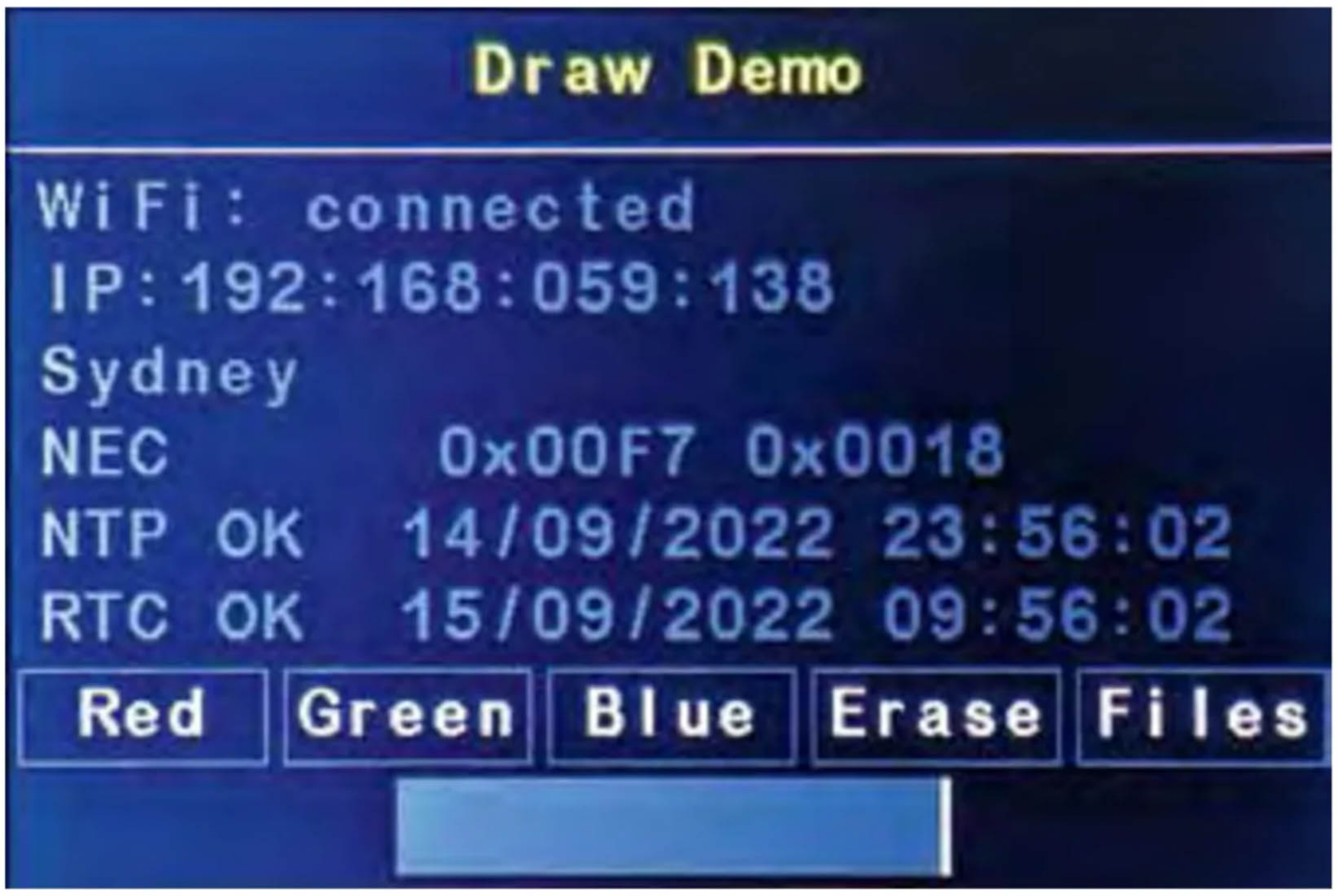
```
#include <WiFi.h>
#include <WiFiUdp.h>
#include <HTTPClient.h>
```

NTP requires the UDP protocol for communication, hence its inclusion. Fetching web pages uses HTTP. Scanning for networks is done by running a single line of code, as is connecting to a network:

```
WiFi.scanNetworks();
WiFi.begin(ssidname,ssidpass);
```

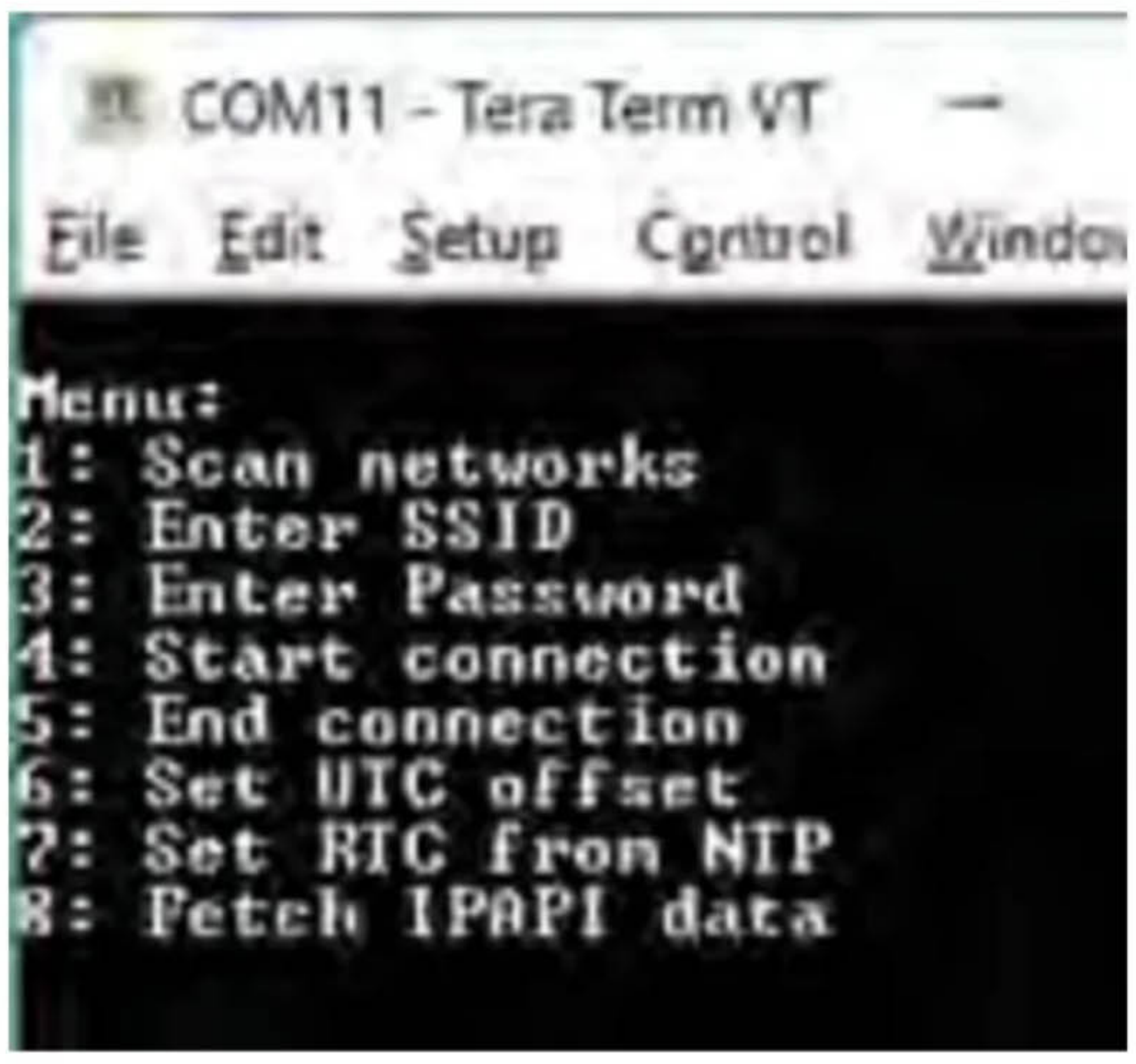
These calls are blocking (ie, the program doesn't proceed until the action is completed), and the latter can take up to ten seconds to run. So they may not suit all applications. The C SDK gives better access to the low-level commands and might be more suited if blocking calls are not desired.

It is possible to use function calls from the C SDK in the Arduino IDE,



```
Draw Demo
WiFi: connected
IP:192:168:059:138
Sydney
NEC         0x00F7 0x0018
NTP OK   14/09/2022 23:56:02
RTC OK   15/09/2022 09:56:02
```

◄ **Screen 1: the Arduino demo for the Pico W has the most features, primarily due to the excellent library support the Arduino community offers. Apart from the new Wi-Fi features, there is now also support for the IR receiver.**



```
Menu:
1: Scan networks
2: Enter SSID
3: Enter Password
4: Start connection
5: End connection
6: Set UTC offset
7: Set RTC from NTP
8: Fetch IPAPI data
```

Screen 2 (right): all the demos include a menu system that can be accessed from a serial terminal program. ▲ This is to simplify entering the Wi-Fi credentials needed for the demo to work. The Arduino output is shown here.

but we preferred to keep the Arduino code consistent with the Arduino way of doing things.

NTP is implemented as a background routine that simply needs to be started and then quietly synchronises in the background. Fetching a website using HTTP can be done in a few lines:

```
http.begin(wificlient,URL);
httpCode=http.GET();
Serial.print(“Return code:”);
Serial.println(httpCode);
if(httpCode == 200)
{
  Serial.println(
    http.getString() );
}
```

We got around some of the longer blocking sections by using the second processor core to do some tasks in the background without interrupting the main program flow. These can be seen in the setup1() and loop1() functions.

At the time of writing, we have not seen an official Arduino board profile for the Pico W, so we were unable to try this out as we did for the Pico. But the Arduino-Pico board profile appears to be updated regularly and works well; we have no hesitation in recommending it.

Using it with the C SDK

Screen 3 shows the LCD panel of the BackPack loaded with the C SDK (software development kit) demo. It includes similar elements to the Arduino example, although the C SDK does not have library support for the IR receiver or RTC chip.

There is an RTC feature in the Pico W (and Pico) that can be used by C SDK, but it doesn't provide the battery backup timekeeping feature that chips like the DS3231 have. It needs the time to be set each time Pico W is reset. Since the Pico W uses a crystal oscillator, it should be pretty accurate once it has been set.

The C SDK performs similar tasks to the Arduino demo, using a Wi-Fi connection and NTP to update the RTC. Location and timezone data are also fetched from **ip-api.com** using HTTP.

Several library files are needed for Wi-Fi support. The first file is required to interface with the Infineon CYW43439 chip that provides the Wi-Fi interface, while the others provide library support for HTTP and NTP:

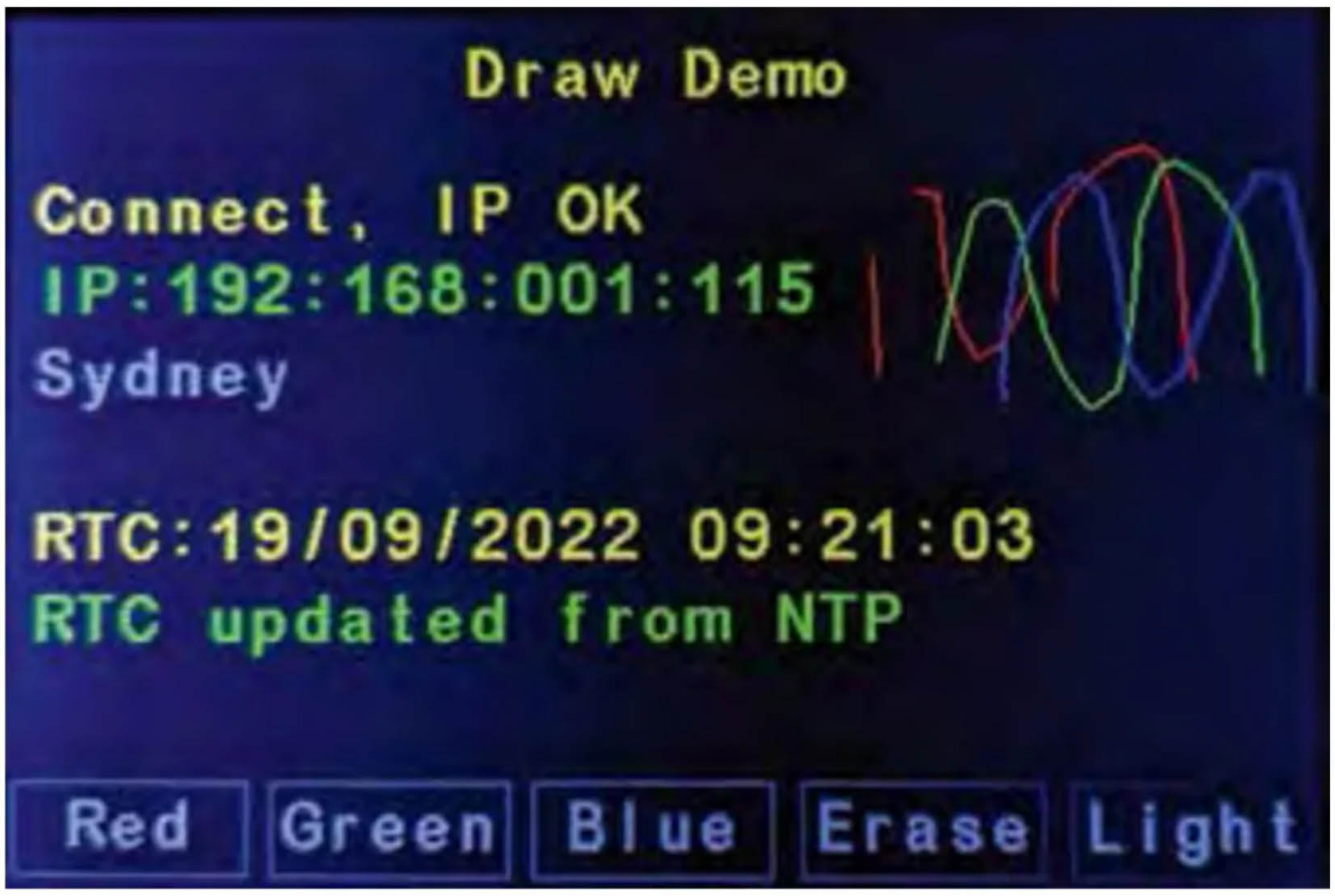
```
#include “pico/cyw43_arch.h”
#include
  “lwip/apps/http_client.h”
#include “lwip/apps/sntp.h”
```

To properly use the C SDK with the Pico W, we had to make a few changes to the **CmakeLists.txt** file, especially in the **target_link_libraries** and **add_definitions** sections. Look at our sample project to see what to do before creating your own projects.

While the C SDK is primarily intended to be used on a Raspberry Pi computer, we ran it on a Windows PC using the pico-setup tool that can be found at **https://github.com/ndabas/pico-setup-windows**

This resulted in many minor glitches, especially as some of the commands are subtly different. If you have a Raspberry Pi computer handy, you might find it more straightforward to program the Pico W via the C SDK.

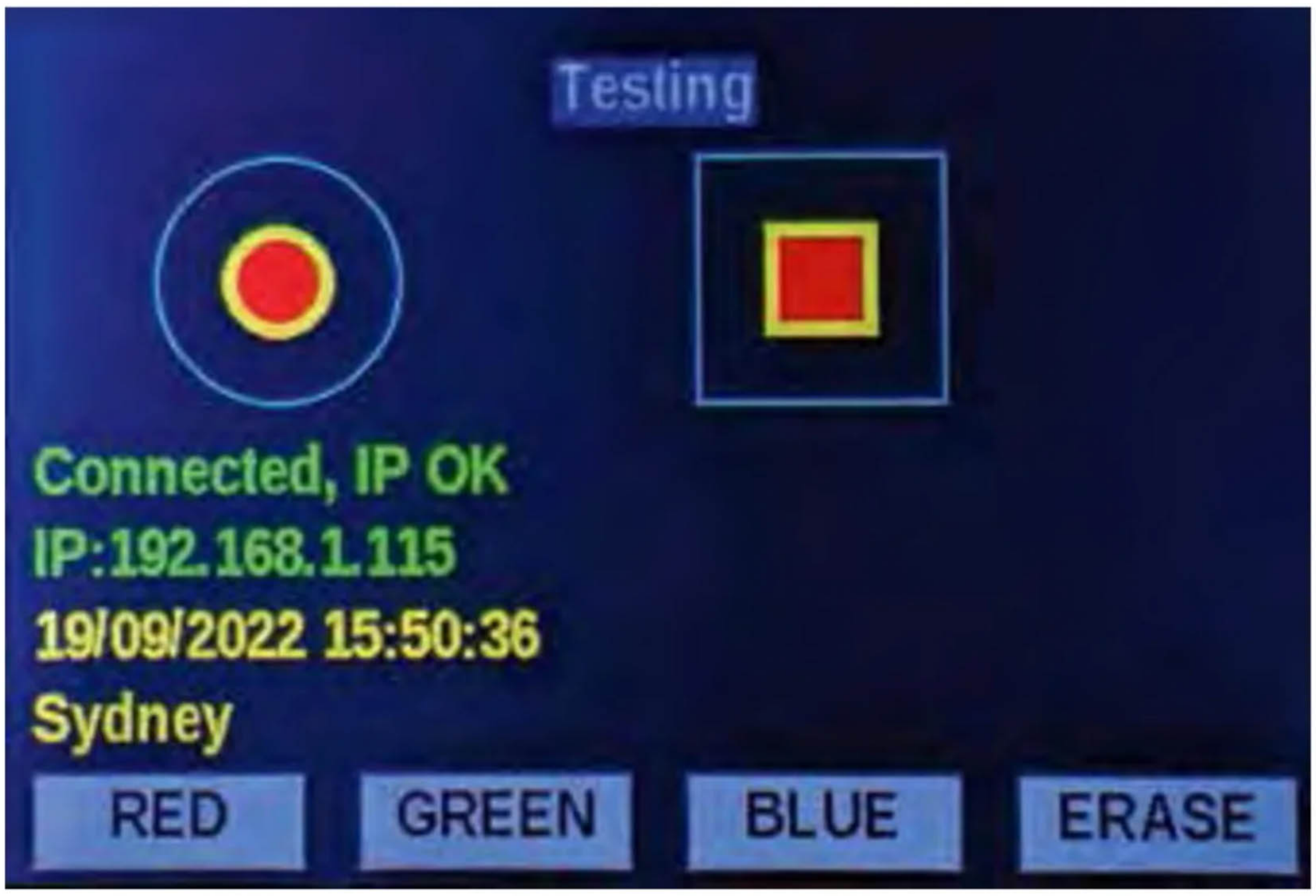
Just as for the original *Pico BackPack* demos, the C SDK software runs very



```
Draw Demo
Connect, IP OK
IP:192:168:001:115
Sydney

RTC:19/09/2022 09:21:03
RTC updated from NTP
```

Screen 3: the C SDK demo runs fast, with good access to low-level functions. Support for protocols like NTP and HTTP is very good once you get it working.



```
Connected, IP OK
IP:192.168.1.115
19/09/2022 15:50:36
Sydney
```

Screen 4: the MicroPython demo has similar capabilities to that of the C SDK. It's possible to use the drawing feature of the demo, but it is not very responsive.

fast and some lower-level functions allow more control than we could easily achieve with the Arduino IDE.

In most cases, the serial port menu is used to start an action, such as starting a network scan or connecting to a Wi-Fi network. These do not return immediately like the Arduino equivalents.

Instead, the main program monitors the status of variables like the Pico W's IP address and displays information as it gets updated in time. This means that the main program is not blocked from other operations while network activity occurs.

Using HTTP requires several callback functions to be set, meaning that using the C SDK can seem a bit more complicated than using the Arduino IDE. Still, if you have the patience to set up and delve into the C SDK, we recommend trying it, especially if you need to get the most performance from your *Pico W BackPack*.

MicroPython

The MicroPython version available for the Pico W at the time of writing is tagged as 'unstable', although we did not have any issues using it. We have included a copy of this version with our software bundle.

Note that there are different MicroPython UF2 files for the Pico and Pico W. Be sure to use the correct version.

Our MicroPython demo has much the same features as the C SDK demo, as shown in Screen 4. We haven't made any changes to the two library files (from the original *Pico BackPack* demo); only the **main.py** file has been updated.

Just like the Arduino IDE, several libraries must be imported to provide Wi-Fi functionality:

```
import network
import urequests
import ntptime
```

We noted that the original MicroPython software was barely fast enough to be useful. The addition of the Wi-Fi features does make interacting with the LCD touch panel quite slow. Still, we expect most people would not try to cram in all the features that we have.

Like the Arduino code, many MicroPython routines are blocking and may not return for many seconds.

The features available are much the same as the C SDK, with options to scan for networks and set the SSID name and password. You can connect, disconnect and make an HTTP request to retrieve data.

Is there Bluetooth support?

Since the Infineon CYW43439 Wi-Fi chip has support for Bluetooth, many people have been left wondering whether the Pico W will be able to use Bluetooth.

At the time of writing, it appears that is not the case. Instead, we are simply left with the tantalising statement from the folks at the Raspberry Pi Foundation that it 'may be enabled in the future'.

Summary

Our demo code does many things you might typically do with a Wi-Fi-capable microcontroller: connect to a network, make HTTP requests to fetch data from websites and use NTP to set the time.

The Arduino IDE (using Arduino-Pico) and MicroPython made this very easy. We found the Arduino IDE more attractive as it has better library support, and the code runs quicker since it uses a compiled rather than interpreted language.

The C SDK was a bit more tricky to work with, but the results are fast and responsive. It also gave us much better access to low-level operations.

Bluetooth will be a nice feature to have when it arrives, but as it stands, the Pico W is very useful at its current price and works very well with the *BackPack* hardware.

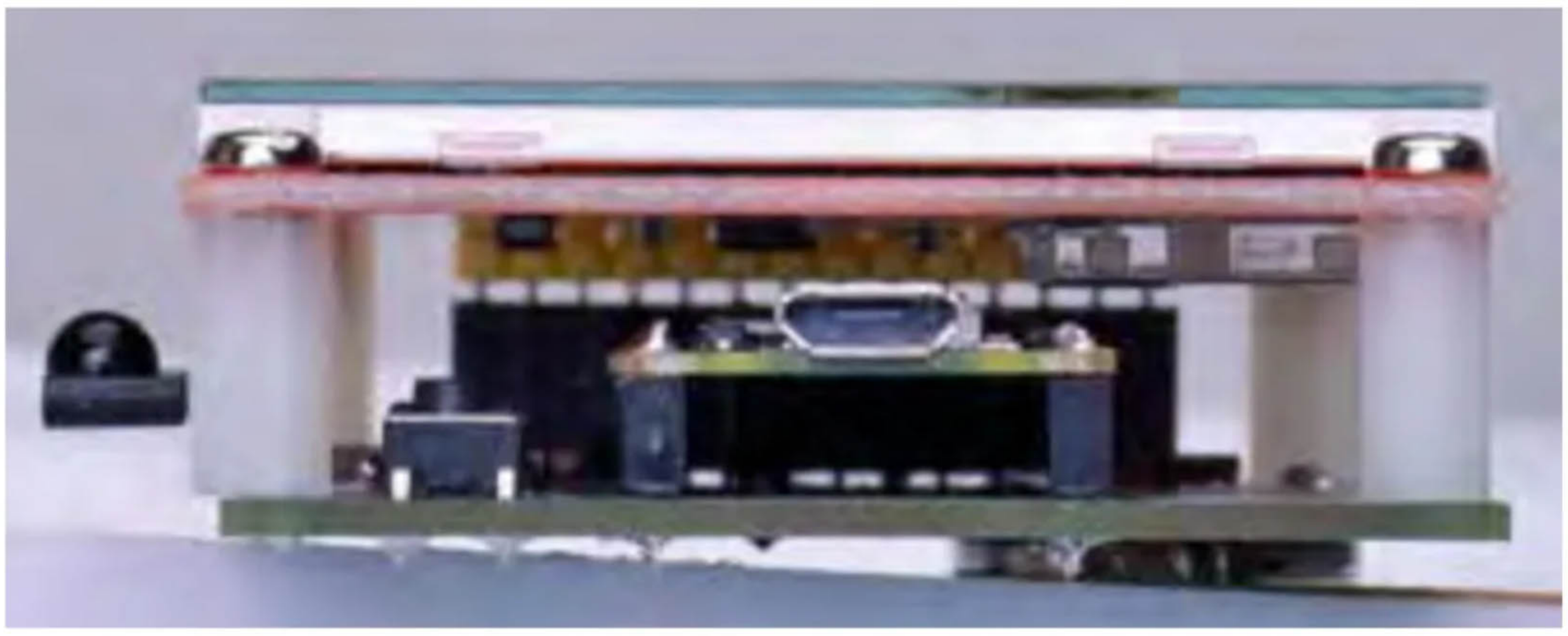
Now that we have Wi-Fi working well with the C SDK, we think the Pico W will be a good choice for future projects needing Wi-Fi. The Arduino IDE will be a handy option when we want to quickly interface with hardware, especially if it needs library support.

Availability

At the time of writing, the Pico W was available from:

- **The PiHut**
  https://thepihut.com
- **Amazon UK**
  https://www.amazon.co.uk/s?k=pico+w
- **Cool Components**
  https://coolcomponents.co.uk/products/raspberry-pi-pico-w
- **Pimoroni**
  https://shop.pimoroni.com

Other retailers include Farnell, element14, Digi-Key and Mouser. Expect to pay around £6.50.



This shows the spacing needed to give clearance for the Pico W's Wi-Fi antenna. Short pin headers are the simplest way to achieve this while also keeping clear of the LCD touch panel, which is mounted above.

HIGH-PERFORMANCE

ACTIVE SUBWOOFER

FOR HI-FI AT HOME

PART 1: BY PHIL PROSSER

This subwoofer is designed to be a no-compromise approach to a 'sub', making it a perfect match for a high-quality home theatre system, or as part of a high-fidelity stereo system.

The Active Subwoofer uses an SB Acoustics SB34SWNRX-S75-6 346mm (12-inch) driver plus a built-in 200W class-AB amplifier module that can deliver up to 180W of continuous output power in this application.

It is a very high-quality sub that you could use in any application. It will provide high-power, extremely low distortion bass for the lower octaves.

Subwoofers are all about moving large volumes of air. The deeper you go into bass frequencies, the more of a challenge that becomes. For true high fidelity, we want a -3dB point well below 30Hz and to achieve solid output to 20Hz.

Unfortunately, we also need to consider real-world practicalities like the physical volume required. That requires us to set aside exotic approaches such as infinite baffles or horn loading.

After modelling quite a few similar drivers, I settled on the SB Acoustics SB34SWNRX-S75-6. When mounted in an 80-litre enclosure tuned to 25Hz, it gives a -3dB point at 25Hz and is only 8dB down at 20Hz in free space. This enclosure is modest for such a hefty driver and for operating to such low frequencies.

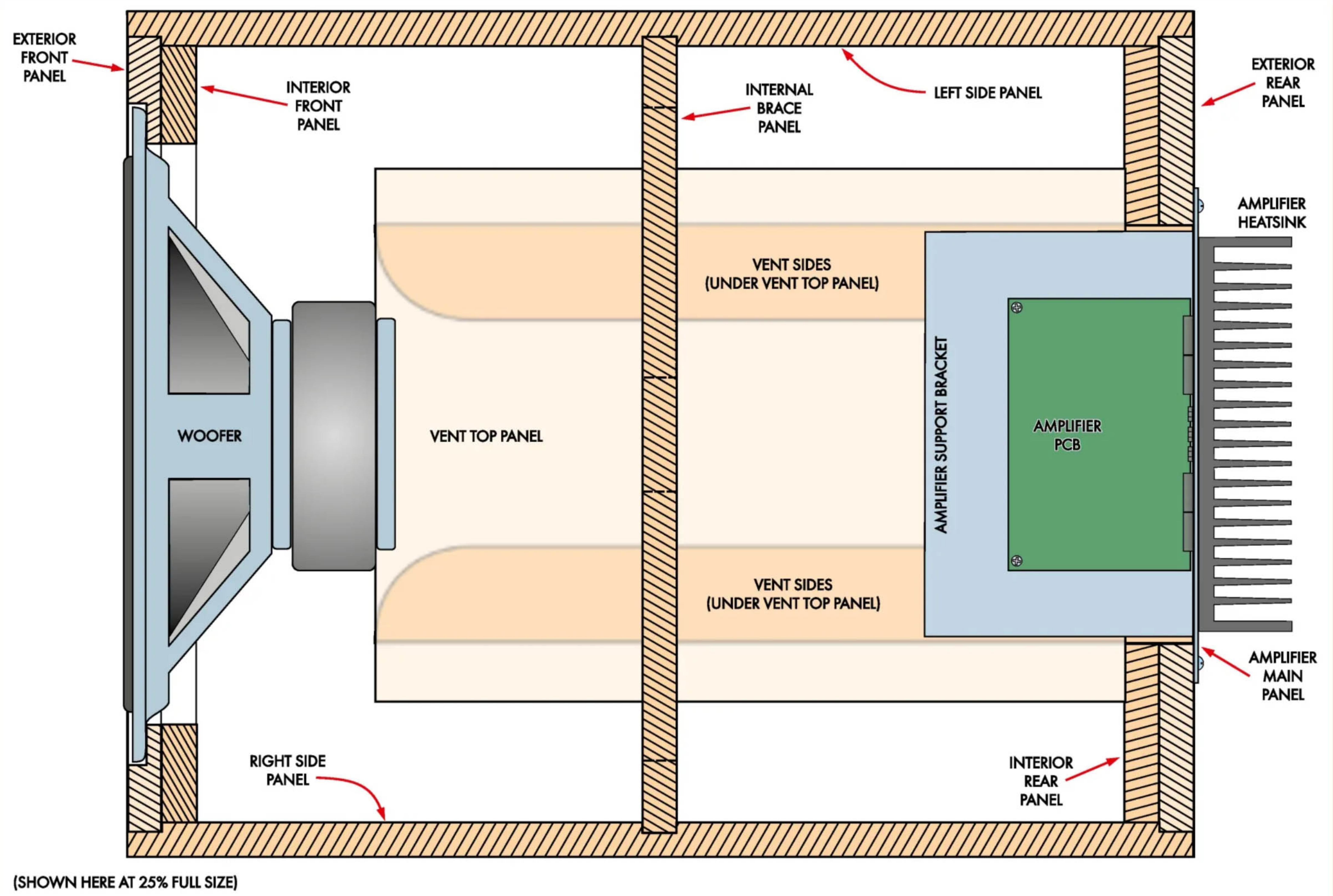

EXTERIOR FRONT PANEL
INTERIOR FRONT PANEL
INTERNAL BRACE PANEL
LEFT SIDE PANEL
EXTERIOR REAR PANEL
AMPLIFIER HEATSINK
VENT SIDES (UNDER VENT TOP PANEL)
WOOFER
VENT TOP PANEL
AMPLIFIER SUPPORT BRACKET
AMPLIFIER PCB
VENT SIDES (UNDER VENT TOP PANEL)
AMPLIFIER MAIN PANEL
RIGHT SIDE PANEL
INTERIOR REAR PANEL
(SHOWN HERE AT 25% FULL SIZE)

Fig.1: a top-down 'X-ray' view of the Subwoofer complete with its integrated 'plate amplifier'.

Parts List – Active Subwoofer

1 assembled plate amplifier – see adjacent panel
1 SB Acoustics SB34SWNRX-S75-6 346mm subwoofer driver **[eg, Willys HiFi: https://willys-hifi.com/products/sb-acoustics-sb34swnrx-s75-6-norex-subwoofer]**
1 2400 × 1200 × 18mm sheet of MDF or similar, cut as per Fig.6
100 50mm-long 8G wood screws (**optional**)
16 35mm-long 8G wood screws
30 28mm-long 8G wood screws
4 100mm diameter thick stick-on felt furniture foot pads
1 3m length of 5-10mm wide soft foam sealing tape (for the driver & plate amplifier)
1 1m × 1m acoustic wadding blanket **[eg, Lincraft 'king size thick wadding']**
1 250mL tube of PVA glue
1 tub of sandable wood filler
1 250mL tin of acrylic primer paint
1 350g can of spray primer paint
1 350g can of spray paint (for two or more top coats)
1 small tube of thermal paste
large quantity of 120, 240 & 400 grit sandpaper (available on 5m reels)

Plate Amplifier
1 assembled SC200, Ultra-LD Mk.3 or Mk.4 amplifier module on 200mm-wide finned heatsink
1 assembled 4-way Speaker Protector with a single relay (January 2023)
1 40-0-40 toroidal transformer, 250VA or 300VA **[Tortech 0300-2-040]**
1 screw-mount IEC mains input socket with integral fuse **[Altronics P8324, Jaycar PP4004]**
1 yellow insulated chassis-mount RCA socket **[Altronics P0219]**
1 miniature 250V AC 6A illuminated DPST rocker switch with solder lugs **[Altronics S3217, Jaycar SK0995]**
1 3-way mains-rated terminal block strip **[Altronics P2130A]**
1 5A 250V slow-blow 3AG fuse **[Altronics S5685, Jaycar SF2232]**
1 35V 400V bridge rectifier **[Altronics Z0091A, Jaycar ZR1324]**
4 8000µF 80V electrolytic capacitors **[Jaycar RU6710]**
1 10nF 63V MKT capacitor
1 270Ω 10% 10W wirewound resistor **[Altronics R0440, Jaycar RR3369]**

Hardware
4 M3 × 25mm panhead machine screws
16 M3 × 16mm panhead machine screws
10 M3 × 6mm panhead machine screws
2 M3 × 6mm countersunk head machine screws
2 15mm-long M3 tapped spacers
5 M3 flat washers
25 M3 shakeproof washers
5 M3 hex nuts
1 260 × 210 × 3mm aluminium sheet
1 377 × 150 × 1.5mm aluminium sheet
1 152 × 72 × 1.5mm aluminium sheet
1 20 × 38 × 1.5mm aluminium sheet (resistor bracket)
1 90 × 70mm sheet of Presspahn or similar insulation
4 blue 6.3mm insulated female spade crimp connectors **[Altronics H2006B, Jaycar PT4625]**
2 3.2-4.3mm solder lugs **[Altronics H1503, Jaycar HP1350]** ***OR***
2 3.7-4mm crimp eye terminal **[Altronics H1520, Jaycar PT4930]**

Wire and Cables
1 1m length of brown 7.5A mains-rated hookup wire **[Altronics W2273, Jaycar WH3050]**
1 1m length of blue 7.5A mains-rated hookup wire **[Altronics W2275, Jaycar WH3052]**
1 10cm length of green/yellow striped 7.5A mains-rated wire (stripped from a mains cord or mains flex)
1 2m length of red heavy-duty hookup wire (0.75mm^2/18AWG) **[Altronics W2270/83, Jaycar WH3040/45]**
1 2m length of black heavy-duty hookup wire (0.75mm^2/18AWG) **[Altronics W2272/84, Jaycar WH3041/46]**
1 2.2m length of green heavy-duty hookup wire (0.75mm^2/18AWG) **[Altronics W2274/85, Jaycar WH3042/47]**
1 2m length of white heavy-duty hookup wire (0.75mm^2/18AWG) **[Altronics W2271/81]**
1 30cm length of red medium-duty hookup wire **[Altronics W2260]**
1 30cm length of green medium-duty hookup wire **[Altronics W2263]**
1 40cm length of shielded/screened audio cable **[Altronics W3010, Jaycar WB1500]**

IMPORTANT!

What you need to build the *Active Subwoofer.*

First and foremost, you need the 'active' element – an amplifier.

At the time of publication this was more complicated than expected. We intended to use the upgrade to the *Ultra LD Mk.2 200W Power Amplifier* published back in August 2010 with the *Mk.3* (or its surface-mount follow-up, the *Mk.4*). However, unfortunately, the 'pandemic silicon shortage' is still affecting a few critical devices for those designs, so they will be published at a later date. Instead, we suggest you use the *SC200 200W Amplifier Module* we published back in 2018 (January to March).

That circuit incorporates most of the features of modern amplifier modules, but uses easy-to-solder through-hole components. There are no tiny surface-mount components.

Do note that just like the *Ultra-LD Mk.3* and *Mk.4* there are component issues for the *SC200*. Fortunately, we have found good alternatives – see the box on the next page.

You will also need the *Multi-Channel Speaker Protector* (4-CH) from *PE*, January 2023, timber for the cabinet and acoustic wadding.

The fantastic thing about this *Active Subwoofer* is that the very extended frequency response does not come at the expense of power handling, and you can safely drive it at very high levels right down to 20Hz. Yes, it is a significant investment to achieve this, but in use, it is truly impressive.

Vented or passive radiator

I have opted to use a slot vent in our *Active Subwoofer*. Passive radiators exist that can be paired with the *Subwoofer*, but they are pretty expensive, and you need two of them! The port is as large as I could fit and has flared

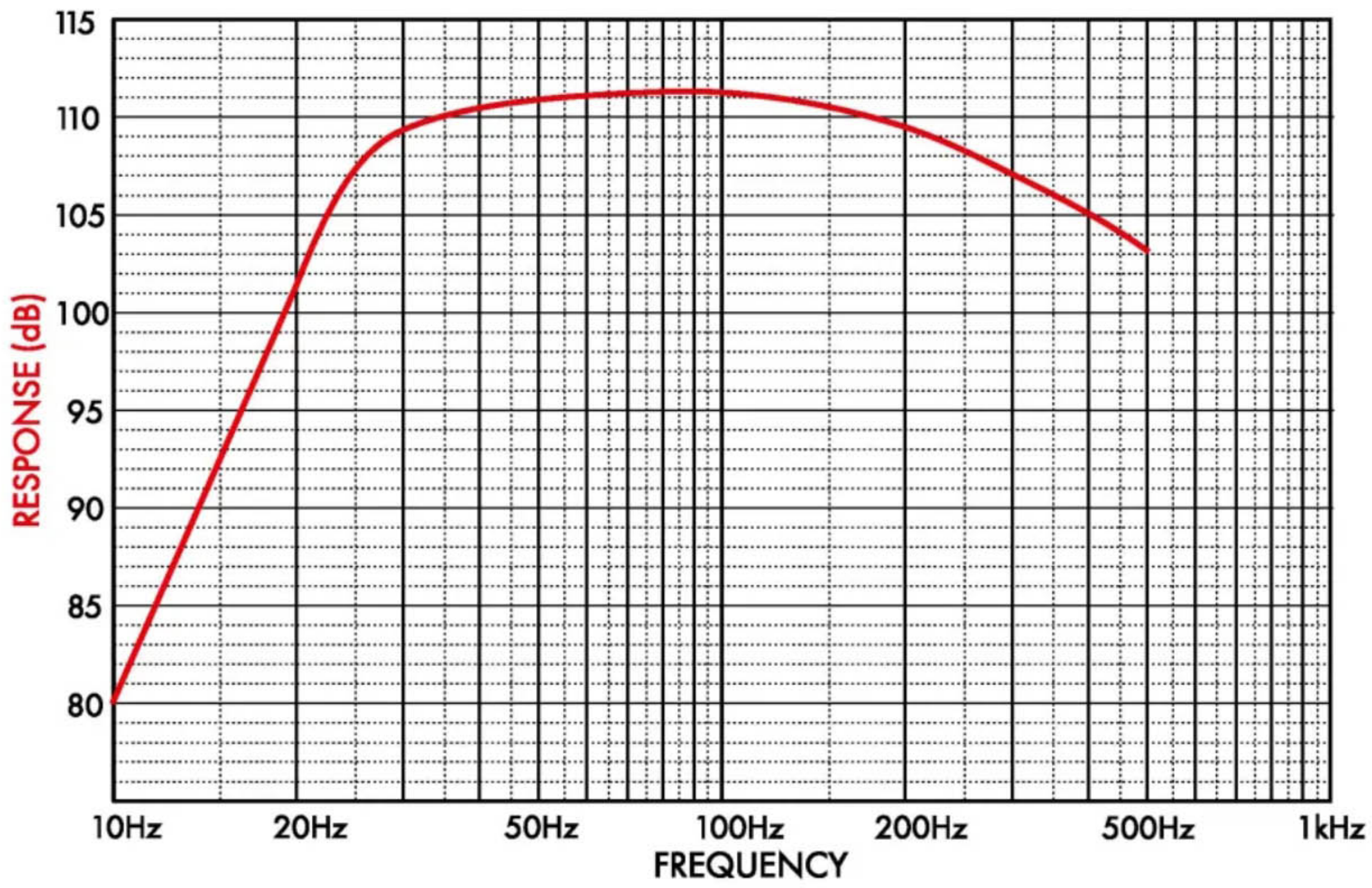


Fig.2: the modelled response of the SB Acoustics SB34SWNRX-S75-6 365mm driver in an 80.5-litre enclosure with a tuning frequency of 25.03Hz.

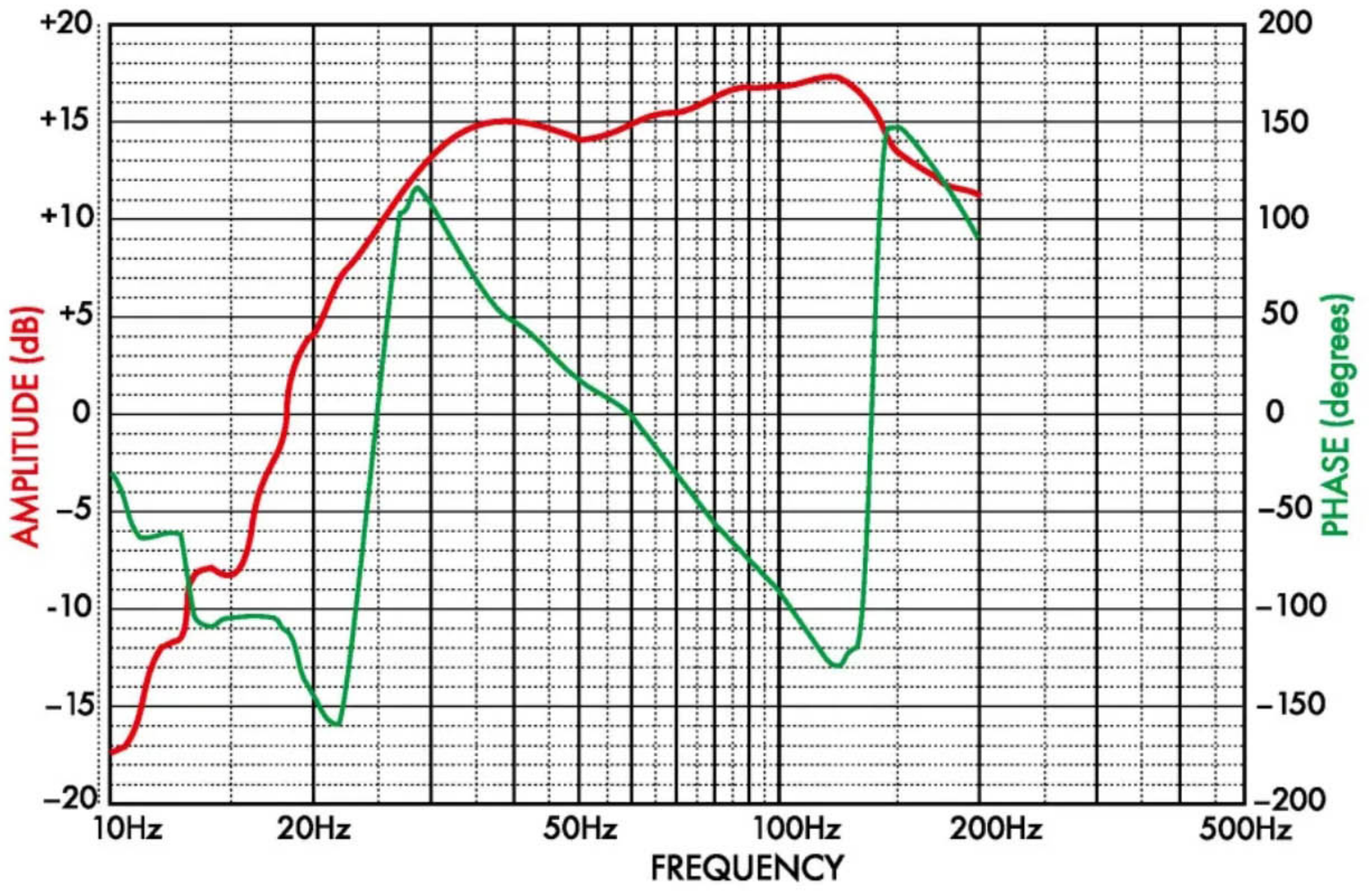


Fig.3: a measurement of the Subwoofer's response outdoors, as far away from sound-reflecting objects as was practical (excepting the ground).

SC200 Amplifier Module components update

Transistors Q8-Q16 may be difficult to source (everything else is standard: small-signal transistors, resistors, capacitors and so on). For the output transistors, Q13-Q16, there are direct equivalents in very similar but not identical packages. FJA4313OTU (TO-3P) is replaced with FJL4315OTU (TO-264) and FJA4213OTU (TO-3P) is replaced with FJL4215OTU (TO-264). The pin spacings are identical and the package sizes are similar, so no changes should be required to the PCB or the heatsink.

The only reason those devices weren't used in the original design is that the TO-3P versions were cheaper and had good enough dissipation for the job (130W for TO-3P; 150W for TO-264). The FJA4313OTU is still available but the FJA4213OTU isn't, and if you're going to change one, you might as well change both.

For the other transistors, KSC2690AYS (NPN) and KSA1220AYS (PNP), luckily there are also excellent direct substitutes although from a different manufacturer. These are the TTC004B (NPN) and TTA004B (PNP). They should drop right in; they are in the same packages with the same pinouts and with virtually identical ratings.

ends to minimise 'chuffing' at high outputs. It is made with stacked layers of MDF cut to form flares at both ends, resulting in a 48-50mm-high, 180mm-wide port.

The vent configuration is shown in the 'X-ray' style overview of Fig.1, along with the amplifier and enclosure, both described below.

If you are not expecting to drive the *Subwoofer* at high levels or very deep, a single 10cm diameter round port of 41cm length will suffice. Still, with the investment this *Subwoofer* represents, I feel that compromising on the port is missing the point.

The amplifier

The integrated amplifier takes its input from an RCA line-level input and delivers about 180W.

The amplifier to use is the *SC200 200W Amplifier Module* (*PE*, January to March 2018). Compatible future amplifiers include the *Ultra-LD Mk.4 Module* (or the *Ultra-LD Mk.3 Module* if you don't like working with SMDs). Just like the *SC200*, both are fine performers in this role.

I have designed a chassis that will suit each amplifier module as they are the same size.

The enclosure

The enclosure is made from 18mm-thick MDF. To provide extra strength and reduce vibration, the front and rear panels are double-layered, and there is a full brace in the middle of the enclosure. The enclosure is 560mm deep, 470mm wide and 470mm tall.

In our loudspeaker system, the *Active Subwoofer* is crossed over at 80Hz with a very steep 24dB/octave slope, so there is no chance of 'hearing' where the *Subwoofer* is located (unless things are rattling around it). If you use it with a home theatre system, then I expect the crossover to be in the 80-150Hz region, which will work fine.

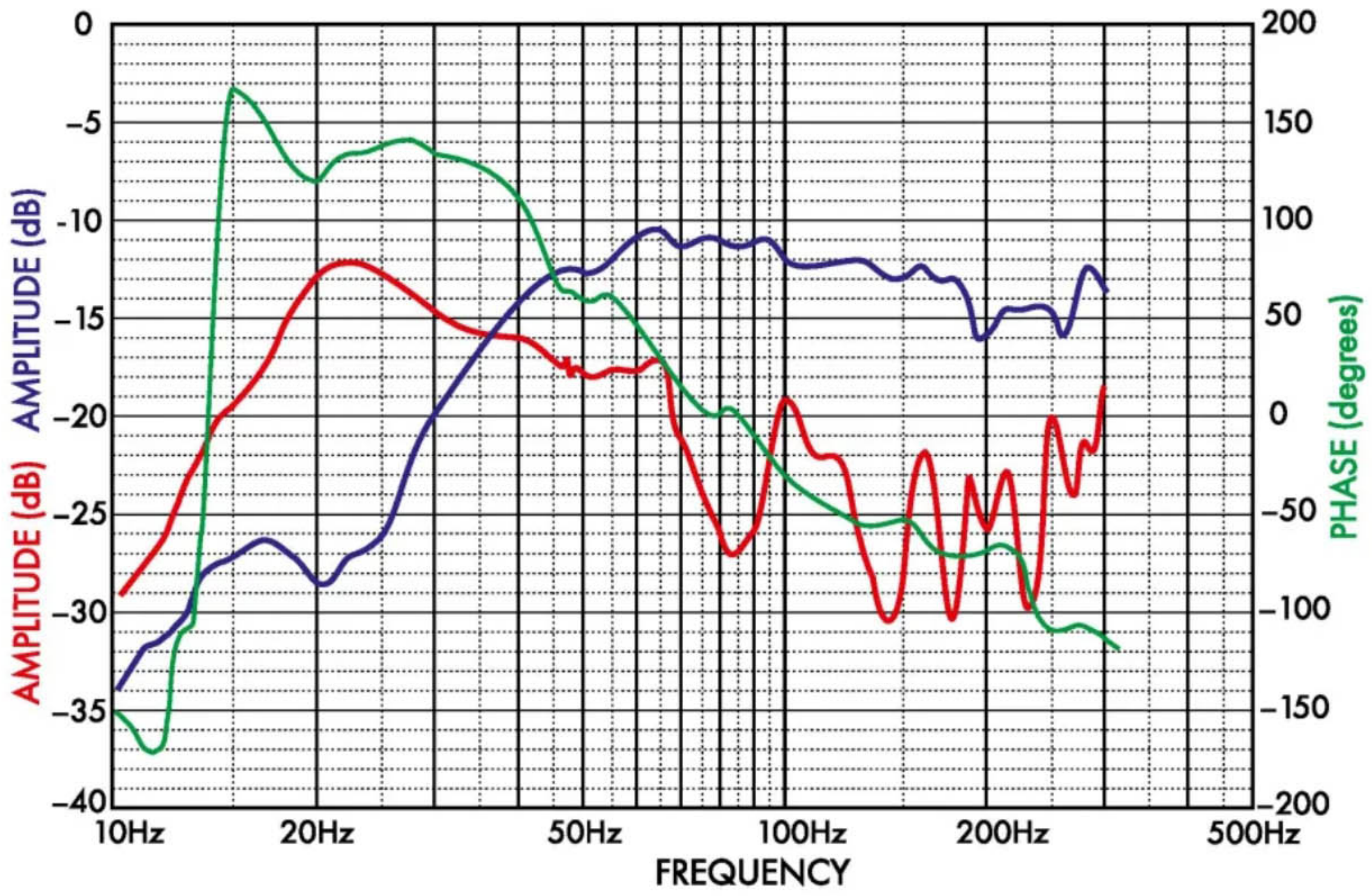


Fig.4: the composite response of the indoor output from the cone (dark blue) and port (red) show they combine to give the predicted response.

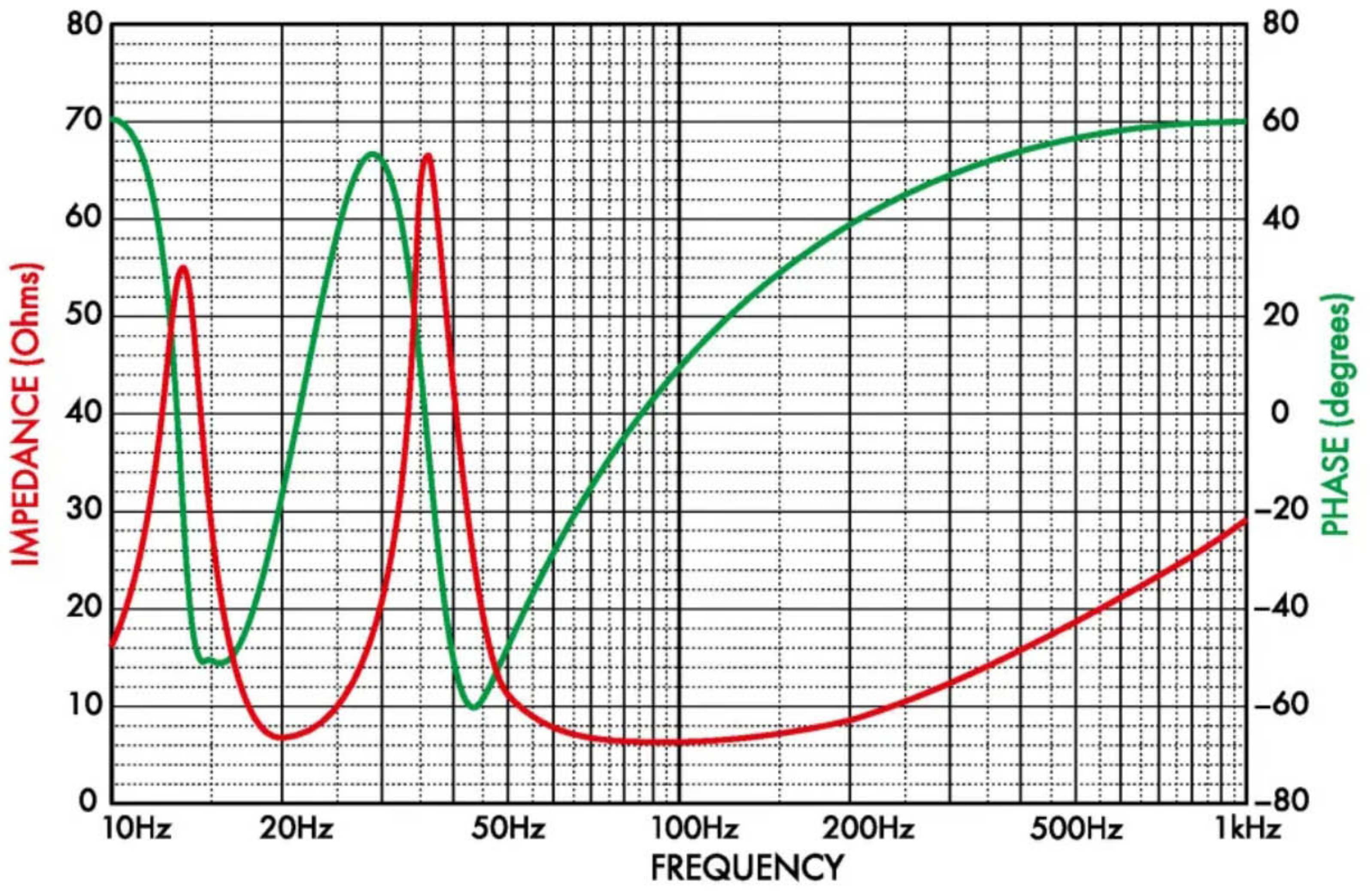


Fig.5: the impedance of the Subwoofer mounted in the enclosure before connecting the power amplifier. The peaks show that our tuning is as predicted.

This size is at the sweet spot where a subwoofer moves from being 'disguiseable' in a home to something you need to work to accommodate. The enclosure is rock solid and capable of both incredible precision and earth-shattering bass.

Performance

Fig.2 shows the modelled (expected) response, while Fig.3 shows the actual measured response. This was made outdoors, about 1.5m from a shed, with the microphone at listening height for the active monitor speakers on 0.8m stands, and at a distance of 1m from the *Subwoofer*.

The measured -3dB point is 27Hz. The subsonic filter for the subwoofer output was active; removing that would extend the bass deeper. There is some ripple in the response, but that is unavoidable without going to great extremes.

The frequency response of subwoofers is tough to measure cleanly indoors due to room resonances and the impact of floors and walls on overall gain. One measurement I took indoors is shown in Fig.4. This is a composite measurement about 20cm from the woofer and port.

'Room gain' is a phenomenon where the resonance of a room increases the output from a subwoofer. This is mainly seen below the frequency at which the room's longest dimension is half a wavelength. For a 10m-long room, that is about 17Hz. Our measured response shows greater output at low frequencies than the Thiele-Small modelling suggests we should see, almost certainly due to room gain.

NOTES:
1. ALL PARTS OF THE SUBWOOFER ARE CUT FROM A SINGLE 1200 x 2400 SHEET OF 18mm THICK MDF, EXCEPT...
2. THE VENT SIDE PANELS SHOULD ALL BE CUT FROM 16mm THICK MDF, OR CUT FOUR FROM 18mm THICK MDF AND TWO FROM 12-14mm THICK MDF.
3. ALL DIMENSIONS ARE IN MILLIMETRES
4. THIS DIAGRAM IS DRAWN TO 10% FULL SIZE

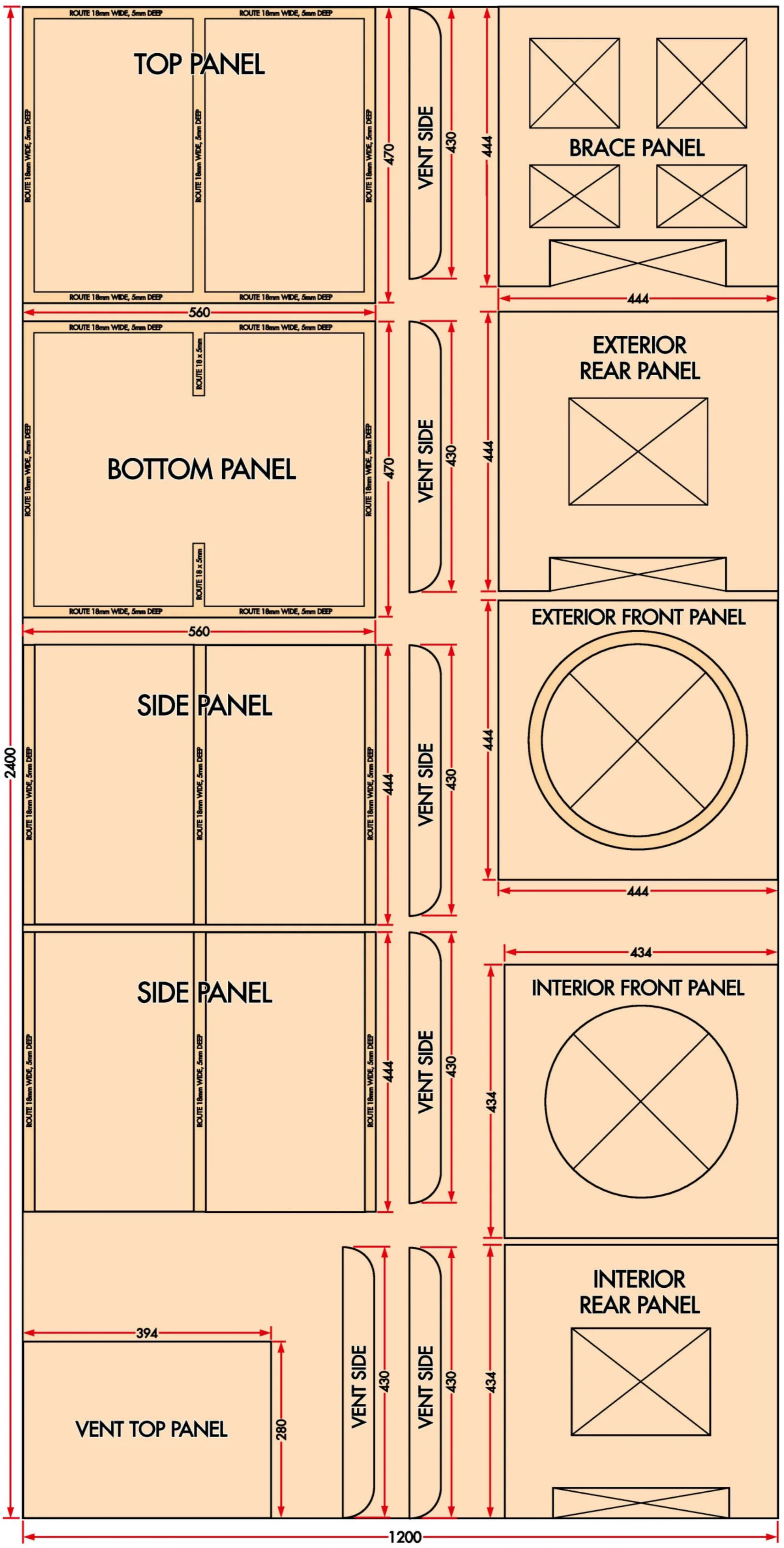

TOP PANEL
BOTTOM PANEL
SIDE PANEL
SIDE PANEL
VENT TOP PANEL
VENT SIDE
BRACE PANEL
EXTERIOR REAR PANEL
EXTERIOR FRONT PANEL
INTERIOR FRONT PANEL
INTERIOR REAR PANEL
ROUTE 18mm WIDE, 5mm DEEP
ROUTE 18 x 5mm
2400
1200
560
470
444
434
430
394
280

Fig.6: these are the subwoofer panel cuts from 18mm MDF when using the recommended rebated joints.

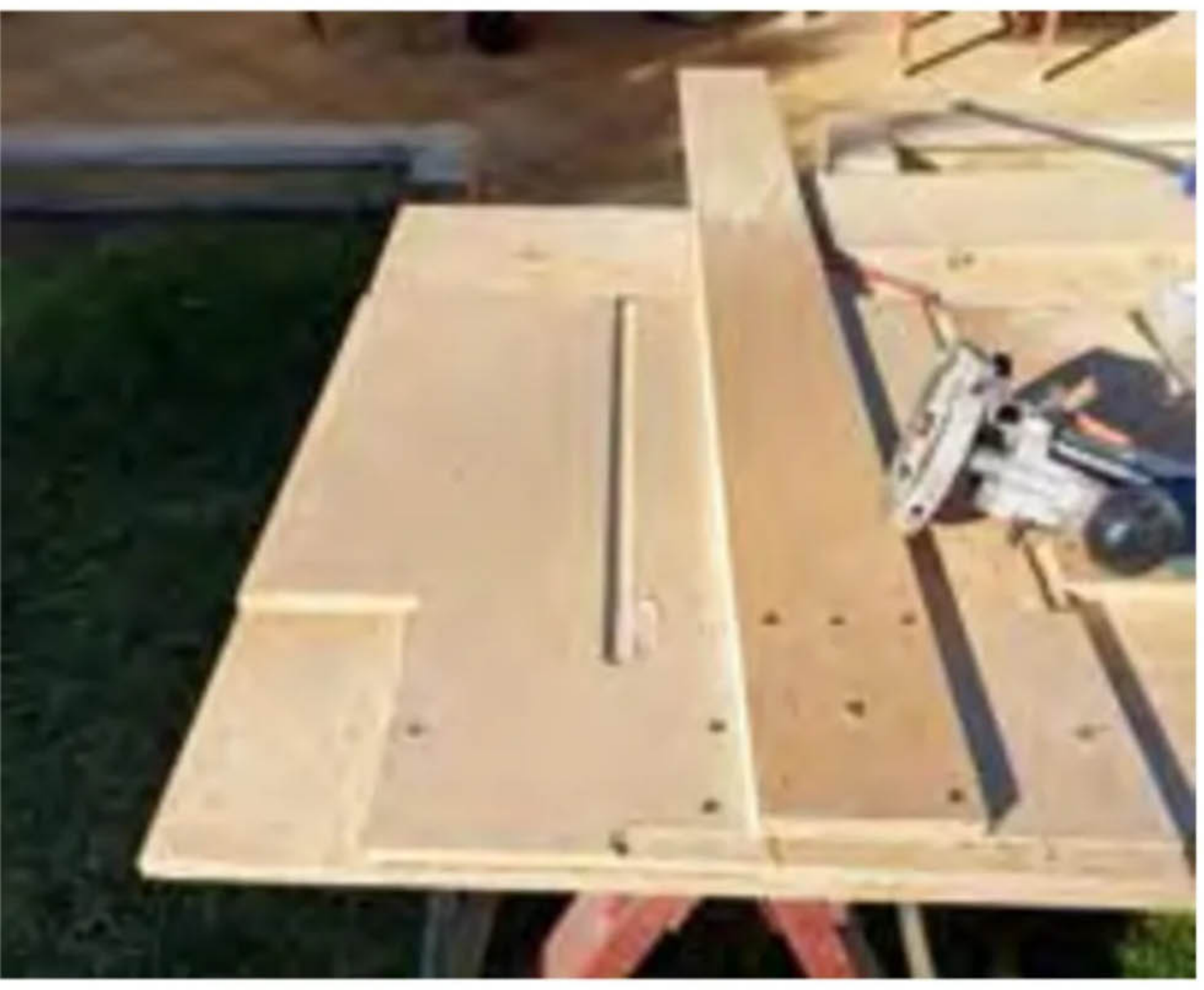


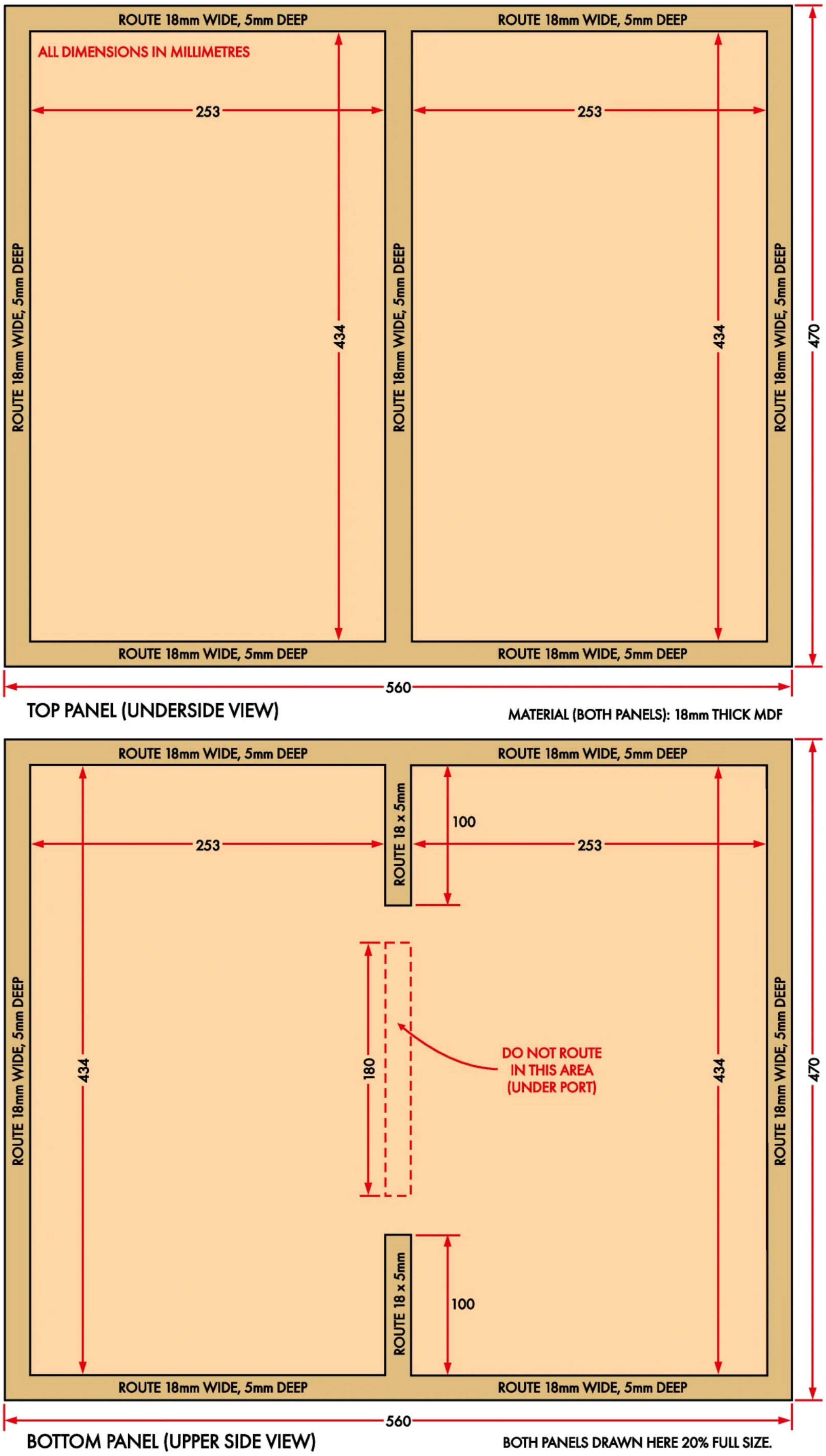
Photo 1: with a router and some MDF off-cuts, you can build a jig to make precisely aligned rebates.

Photo 2: My home-made circle jig allowed me to create a clean circular rebate and cut out the driver hole perfectly.

Photo 3: the stack of panels after the rebates and holes have been made. The vent sides are on the top of the pile (and shown below). They are made from three layers of stacked MDF glued together and sanded smooth.

Photo 5: it's critical to 'dry fit' everything together before applying glue. If you start gluing and find a problem, it will be (much) harder to fix.

The *Subwoofer's* impedance curve is shown in Fig.5. It is well within the handling capabilities of the amplifiers we are using and low enough to get almost the full 200W available into the driver.



ROUTE 18mm WIDE, 5mm DEEP
ALL DIMENSIONS IN MILLIMETRES
253
434
470
560
TOP PANEL (UNDERSIDE VIEW)
MATERIAL (BOTH PANELS): 18mm THICK MDF
ROUTE 18 x 5mm
100
180
DO NOT ROUTE IN THIS AREA (UNDER PORT)
BOTTOM PANEL (UPPER SIDE VIEW)
BOTH PANELS DRAWN HERE 20% FULL SIZE.

Fig.7: details of the rebates routed in the top and bottom panels (all 5mm deep). Other than that, they are simple rectangles of MDF.

The enclosure

There are many ways you can build the enclosure. Fig.6 shows how you can cut all the panels from a single 2400 × 1200mm sheet of 18mm-thick MDF while minimising the number of cuts. I did it that way as I don't have a table saw and wanted to get the sheet cut at the local hardware store where I purchased it.

This proved very successful, and in less than 15 minutes, I had all the major panel cuts done and the panels within 1mm of the specified size. The whole lot then fit in the back of the VW Golf to get it home. The tools you will need to finish the raw panels include a router, jigsaw, cordless drill or hand tools and a lot of elbow grease.

Review the drawings before you proceed; detailed views of the cut panels are shown in Figs.7-12. I used routed rebates for all panel joints that allow you to simply glue and clamp the enclosure together if you have many

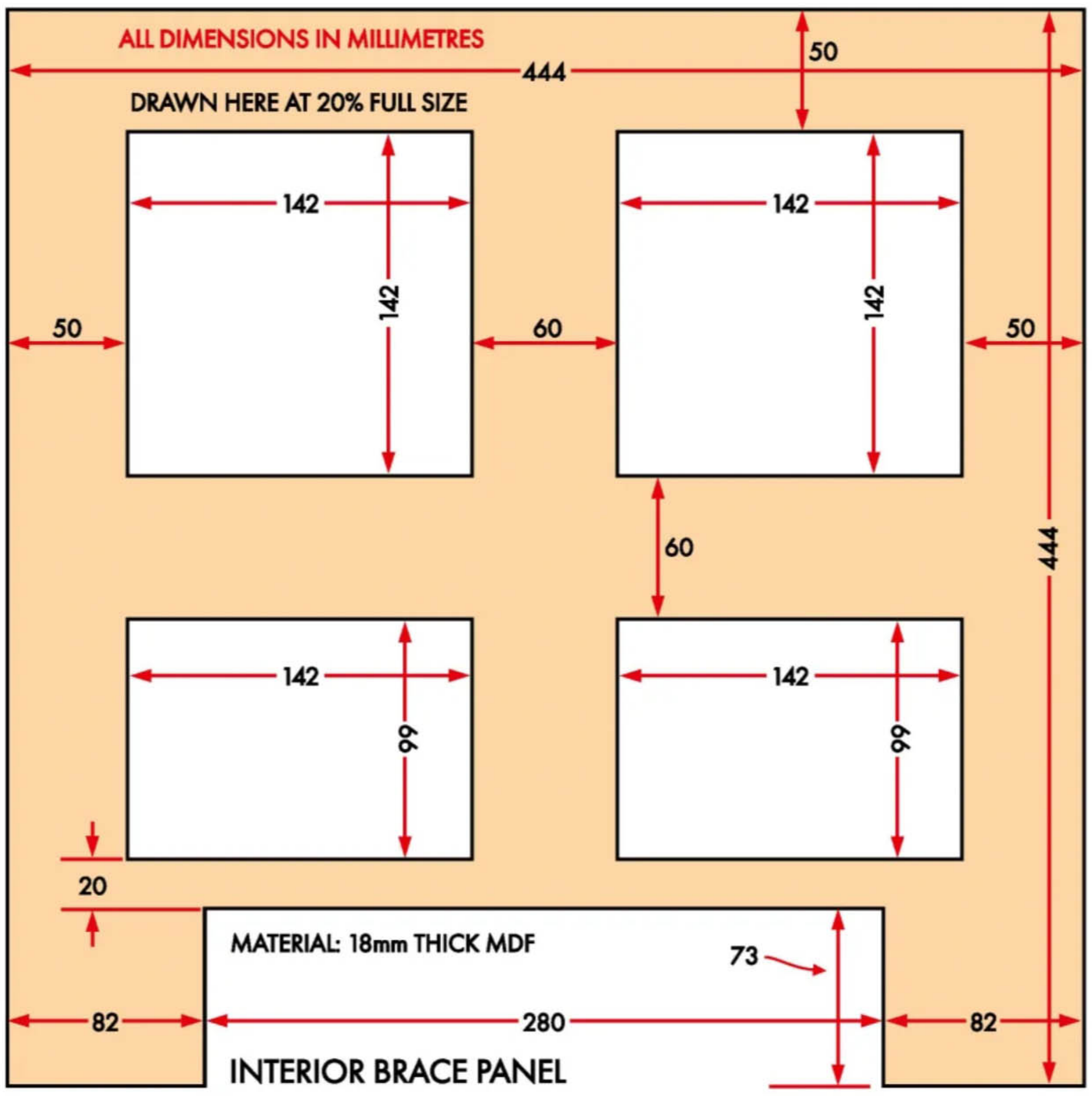

ALL DIMENSIONS IN MILLIMETRES
DRAWN HERE AT 20% FULL SIZE
444
50
142
142
142
142
50
60
50
60
444
142
99
142
99
20
MATERIAL: 18mm THICK MDF
73
82
280
82
INTERIOR BRACE PANEL

Fig.8 (left): here's how to make the internal brace. The sizes and shapes of the holes don't need to match mine exactly but make them reasonably close to get the specified performance.

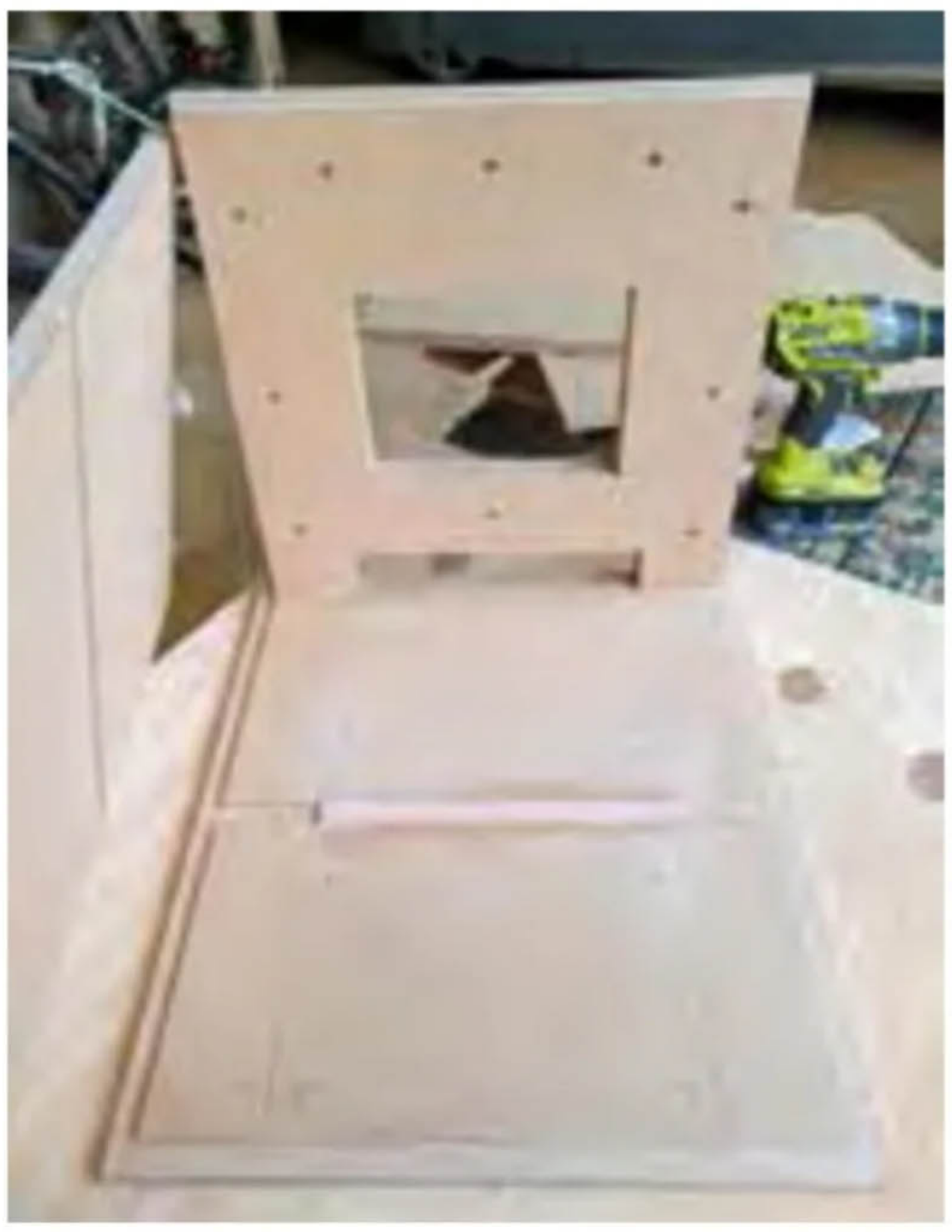
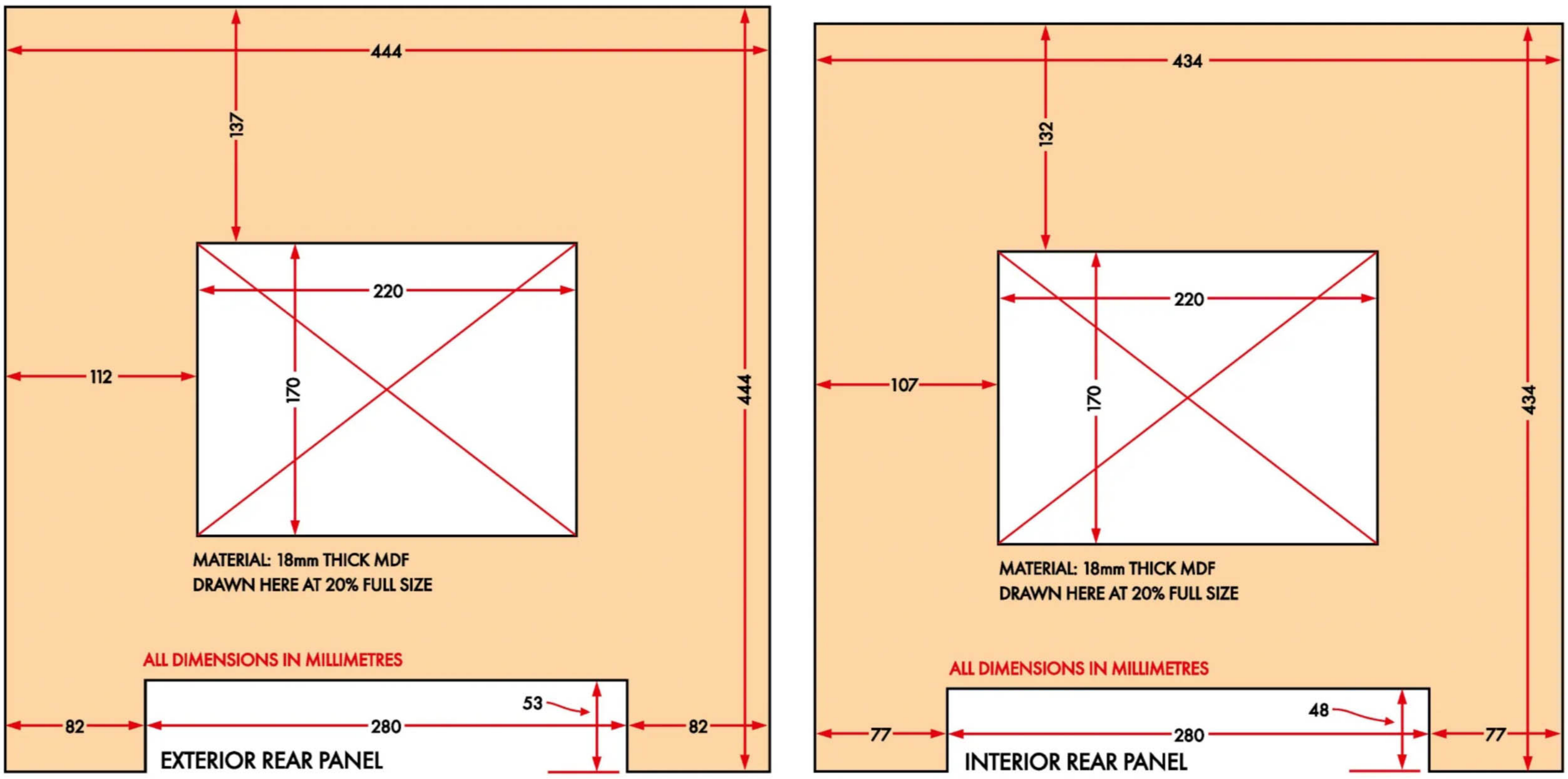


Photo 6: installation of the rear panels. I routed straight across the bottom panel, then filled the rebate with wood filler in the port area.

Fig.9 (below): the rear panel is made of two pieces of MDF glued together, one slightly smaller than the other.


444
137
220
112
170
444
MATERIAL: 18mm THICK MDF
DRAWN HERE AT 20% FULL SIZE
ALL DIMENSIONS IN MILLIMETRES
53
82
280
82
EXTERIOR REAR PANEL
434
132
220
107
170
434
MATERIAL: 18mm THICK MDF
DRAWN HERE AT 20% FULL SIZE
ALL DIMENSIONS IN MILLIMETRES
48
77
280
77
INTERIOR REAR PANEL

sash clamps. This routing can be done very simply using a jig, described below. You will also need to cut out the holes for the port and amplifier module, and rebate the driver hole.

If you don't like the idea of using a router, you could resize the panels and screw them together as butt joints. You will see in the photos that I used screws as well as rebates. That was to make assembly clear and simple for Zak, my 9-year-old helper who was over for the weekend. He really wanted to get involved and, between us, gluing and screwing the rebated panels went very well.

My suggested numbered assembly steps are as follows.

1. Purchase the MDF panel and get it cut into the main pieces. This should be a fair stack of timber.
2. Route the panels as shown in the panel routing figures (Figs.7, 10 and 11). By screwing an off-cut of 18mm MDF to your worktop and a straight-edged off-cut at 90° to it, you can make an extremely effective routing jig into which the 18mm panels fit perfectly, as shown in Photo 1.

   Using this jig and an end stop, there is no need for measuring and fiddling to route the brace as the rebates are all at the same depth (5mm). Similarly, you can route the rebates on the end panels using this jig to ensure everything is square.
3. Make the driver hole. I used a circle jig made from an aluminium off-cut. I made several holes in it to get the diameter of the rebate hole and driver cut-out just right, testing with the driver to ensure they were correct. The result is shown in Photo 2.

   The driver rebate is 10mm to ensure the frame sits flush with the front panel.
4. Cut out the vent holes and holes in the brace. I used a jigsaw.
5. Cut out the vent sides and flares, glue them together and fill and sand them smooth. I used some 'bog' I found in the shed; any sandable filler will work. Don't use acrylic filler as it will not sand! It does not need to be super smooth, but I did want to smooth over some of my less spectacular jigsaw cuts.

Assembly

With the panels made, as shown in Photo 3, it's time to assemble them

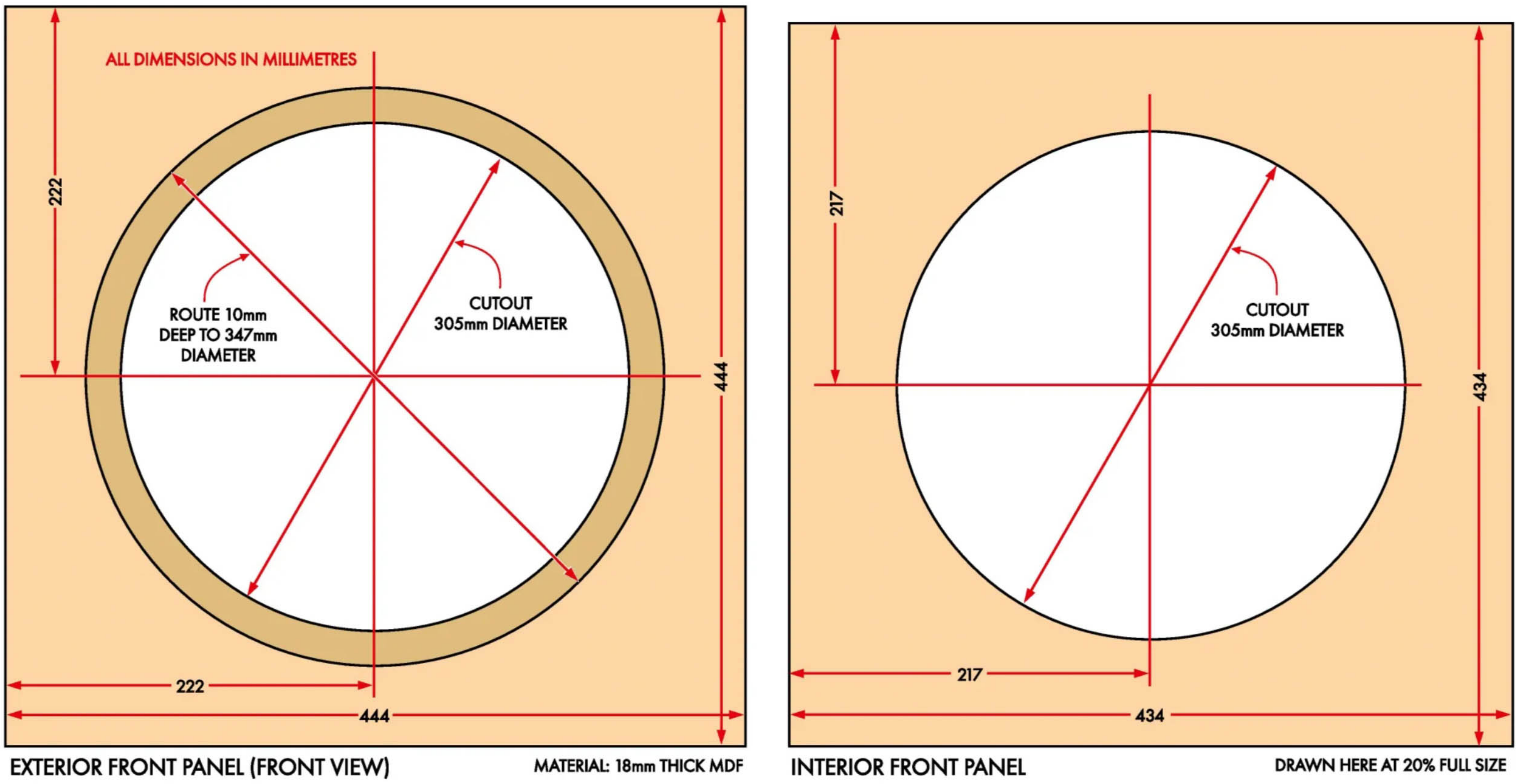

ALL DIMENSIONS IN MILLIMETRES
222
ROUTE 10mm DEEP TO 347mm DIAMETER
CUTOUT 305mm DIAMETER
444
222
444
EXTERIOR FRONT PANEL (FRONT VIEW)
MATERIAL: 18mm THICK MDF
217
CUTOUT 305mm DIAMETER
434
217
434
INTERIOR FRONT PANEL
DRAWN HERE AT 20% FULL SIZE

Fig.10: similar to the rear panel, the front panel is two pieces of MDF glued together. See our hints on how to make a jig to route the circular rebate and cut the hole neatly.

using the following steps. Fig.13 is a side 'X-ray' view of the *Subwoofer*, which might help you understand how it all goes together.

1. Do a 'dry fit', as shown in Photo 5. Take all the pieces and assemble the enclosure without glue or screws. Use masking tape to hold the panels together. You need to be sure that everything fits and that there are no unmanageable gaps. If you need to file or trim any panels, now is the time, as a good job is almost entirely in the preparation.
2. If you plan to use screws and glue, drill and countersink the holes to accommodate the screws. A 4mm drill is about the right size. When assembling the box, you will want to use a 3mm drill to make pilot holes for the screws in the end grains. This might seem like a large pilot hole, but the 50mm screws will be totally secure, and you will experience no splitting of the MDF.
3. Install the rear panels. This step requires the rear exterior and interior panels to be attached to the base. First, sit the two rear panels in the rebate and then dry-fit the side panels to ensure the alignment of the rear panels is good. Screw the rear interior and exterior panels together using 35mm-long 8G screws with PVA adhesive between the panels. Make sure they are held tightly together.

   Now align this on the base panel, ensuring the two side panels fit perfectly. Screw this to the bottom panel.
4. Attach the sides and the port braces. To get the left side perfectly aligned, drill pilot holes for the screws in the right spots and screw and glue it in. Then fit the brace pieces so they are flush on the rear exterior panel. Make sure they

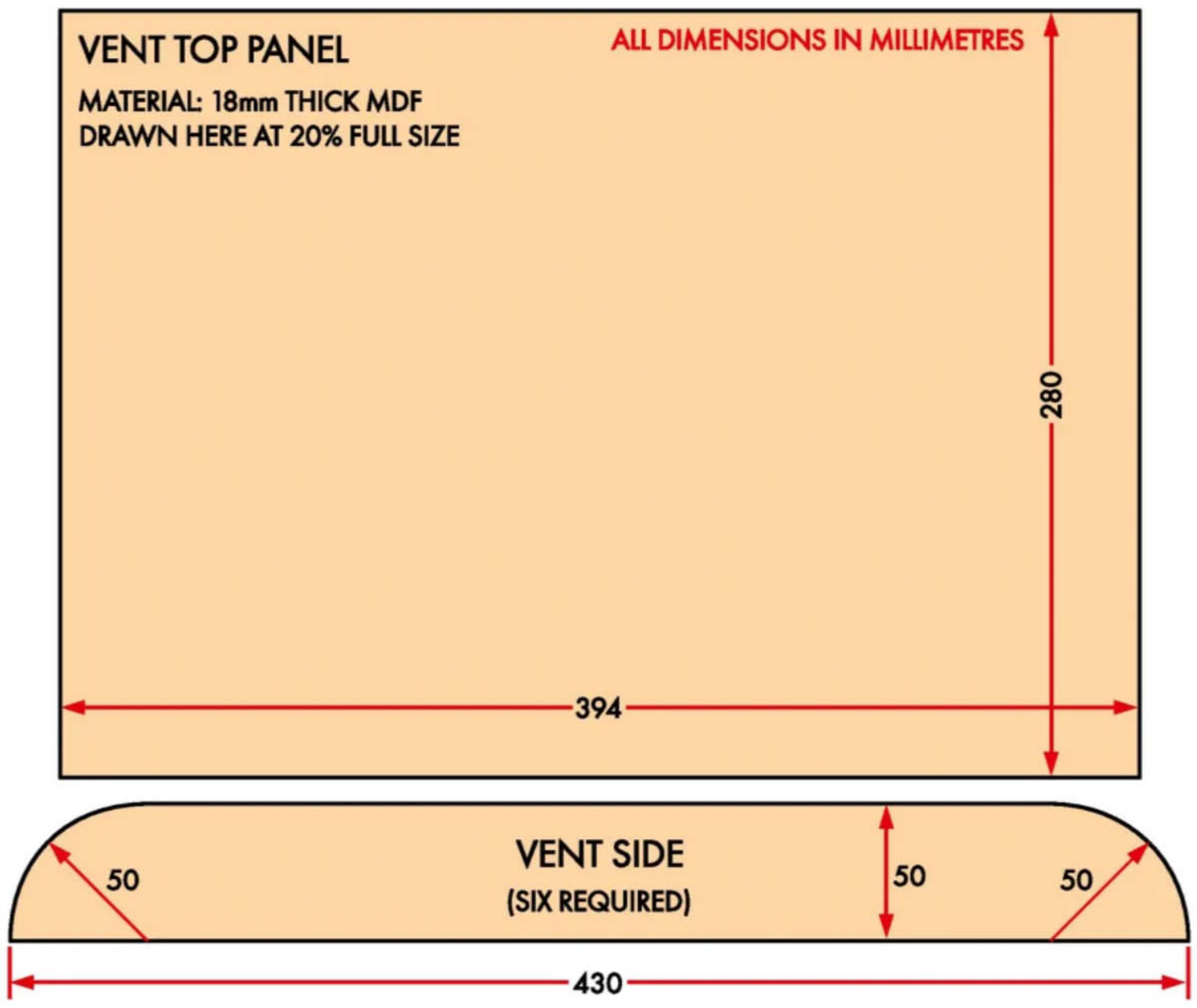

VENT TOP PANEL
MATERIAL: 18mm THICK MDF
DRAWN HERE AT 20% FULL SIZE
ALL DIMENSIONS IN MILLIMETRES
280
394
VENT SIDE
(SIX REQUIRED)
50
50
50
430

Fig.12: the vent is made from these pieces, but note that you should cut the six side pieces from 16mm MDF to get the required 48-50mm total thickness for three pieces, or use four cut from 18mm MDF and two from 12mm MDF (18mm × 2 + 12mm = 16mm × 3 = 48mm).

Photo 7: at this point, all the panels except the top have been attached.

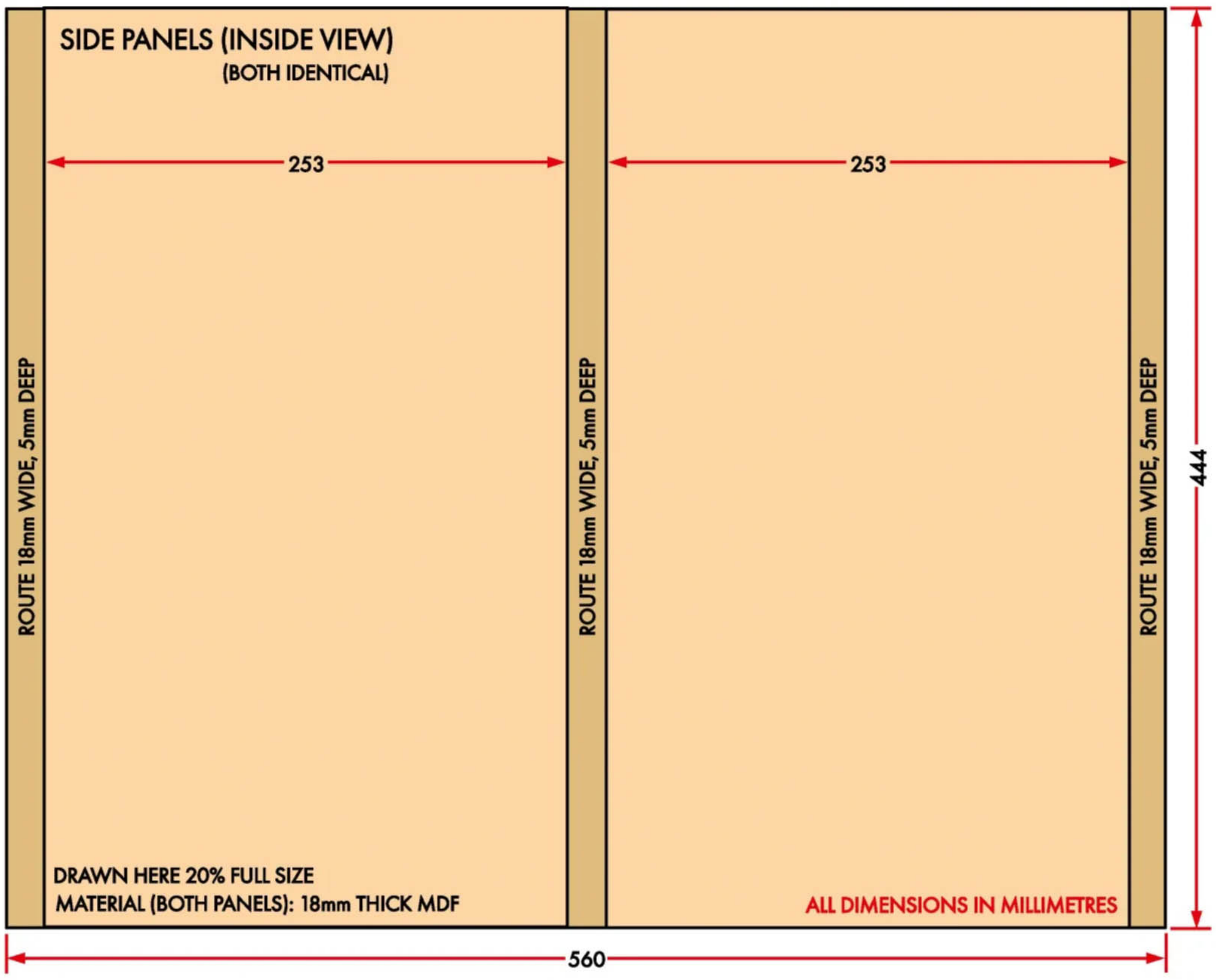

SIDE PANELS (INSIDE VIEW)
(BOTH IDENTICAL)
253
253
ROUTE 18mm WIDE, 5mm DEEP
ROUTE 18mm WIDE, 5mm DEEP
ROUTE 18mm WIDE, 5mm DEEP
444
DRAWN HERE 20% FULL SIZE
MATERIAL (BOTH PANELS): 18mm THICK MDF
ALL DIMENSIONS IN MILLIMETRES
560

Fig.11: the two side panels are identical and have a central 5mm rebate (for the interior brace) and one at each end (where the front and rear panels will join).

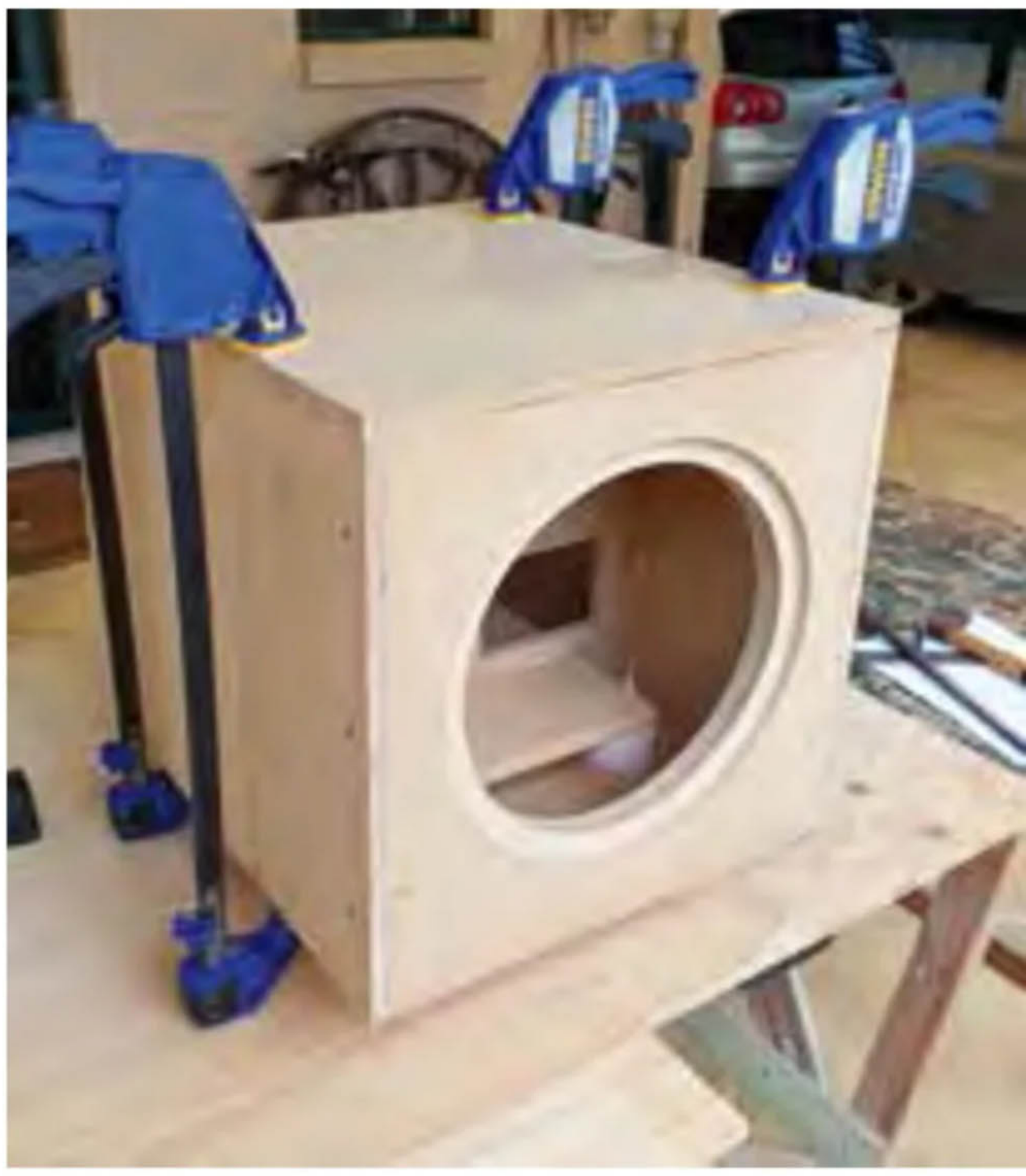


Photo 8: after installing the top panel, I applied clamps liberally and waited for it to dry. You can see the exit of the port and the flush fit of the brace to the top panel of the port here.

   are parallel inside the enclosure and secure them. Finally, install the right-hand panel.
5. Install the internal brace and front panels. First, glue and screw down the panel that forms the top of the port. The internal brace and front panels should slide straight into place in their rebates. If not, adjust them until they are a perfect fit. Glue and screw them in.
6. Finally, attach the top panel (Photos 7 and 8). Make sure any glue that squeezes from the joints is cleaned up as once dry, it is hard to remove.

Finishing the enclosure

I chose to paint the *Active Subwoofer*, the key steps being:

1. Rout the corners with a 6mm radius router to make the edges neat, smooth and pleasant to handle.
2. Seal the enclosures with acrylic primer applied with a roller.
3. Sand the enclosure lightly to get rid of any gross roughness.
4. Fill all screw holes and end grains with filler, ensuring not to put too much. That would be a terrible mistake to make; a thick layer of filler is very hard to sand down.
5. Sand it smooth (Photo 9).
6. Repeat the filling and sanding until the surface is perfect.
7. Prime again, sand and paint for final finish (Photo 10).

The subwoofer amplifier

I built the amplifier and mounted it with a suitable power supply on an aluminium plate. I chose my amplifier to deliver close to 180W continuous into our 6Ω subwoofer driver.

I fabricated a bracket and panel to accommodate the amplifier and all parts to make a stand-alone module, that slips into a 220 × 170mm cut-out in the Subwoofer's rear panel. This includes the following:

- One *SC200* (or: *Ultra-LD Mk.3* (mostly through-hole) or *Mk.4* (mostly SMD) amplifier module)
- The *Multi-channel Speaker Protector* (with one channel used)
- A 250-300W power supply
- Heatsinking, switching and protection

Refer to the January to March 2018 issues of *PE* for details on the *SC200 Amplifier Module*.

The *Multi-channel Speaker Protector* we're using was described in the January 2023 issue of *PE*. The only change from those instructions is to install just one relay on the *Speaker Protector* as we are running it from ±57V rails. Using only one relay halves the dissipation in the regulator, and we only have one channel to protect.

I used a 3mm-thick panel of aluminium as the main plate for the chassis. To that, I mounted a folded bracket made from 1.5mm-thick

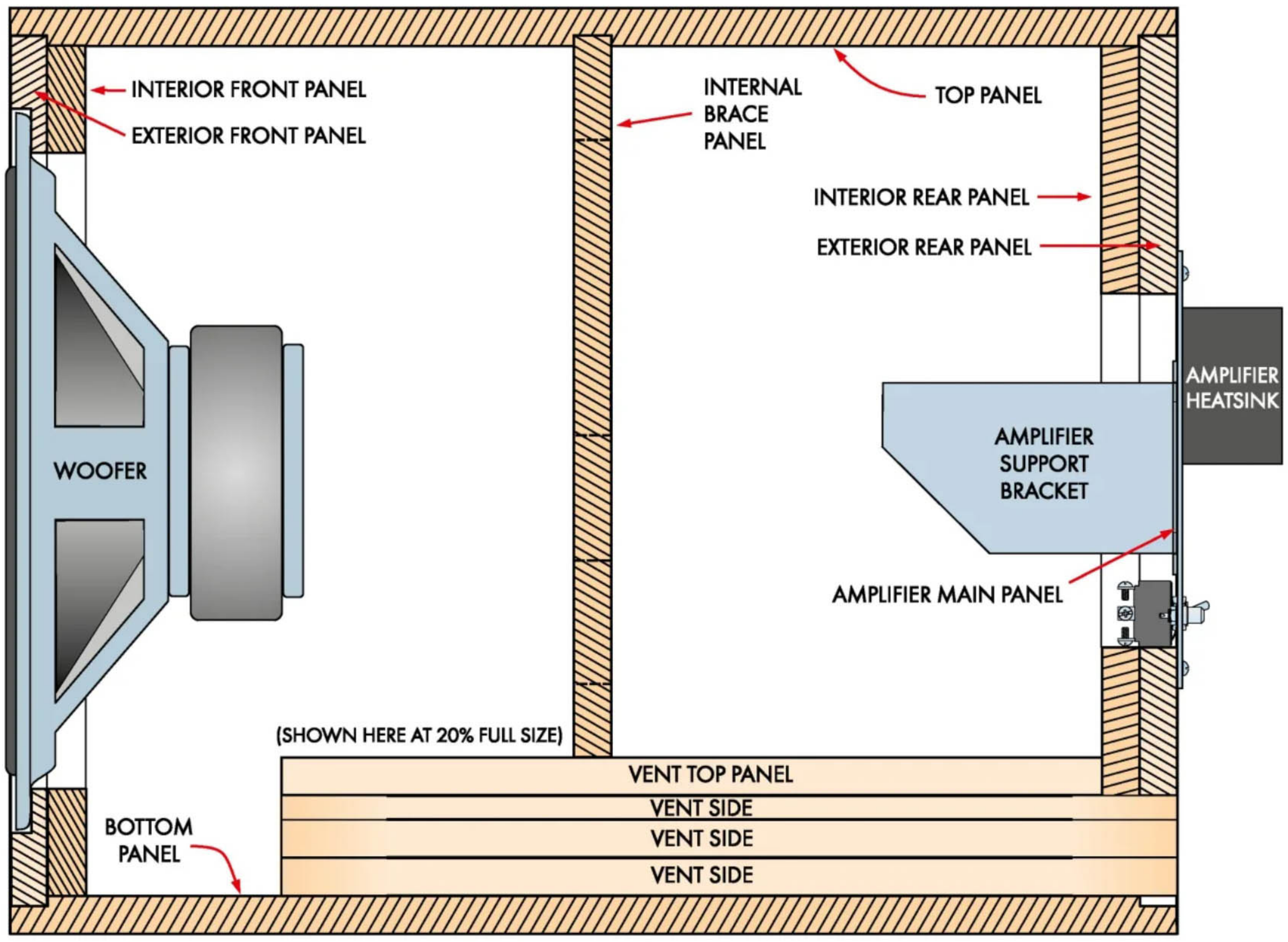

INTERIOR FRONT PANEL
EXTERIOR FRONT PANEL
INTERNAL BRACE PANEL
TOP PANEL
INTERIOR REAR PANEL
EXTERIOR REAR PANEL
AMPLIFIER HEATSINK
WOOFER
AMPLIFIER SUPPORT BRACKET
AMPLIFIER MAIN PANEL
(SHOWN HERE AT 20% FULL SIZE)
BOTTOM PANEL
VENT TOP PANEL
VENT SIDE
VENT SIDE
VENT SIDE

Fig.13: an internal side view of the finished Subwoofer without the side panels.

aluminium for the transformer and an L-shaped panel for the speaker protector.

Next month

We don't have enough space to fit the construction details of the internal amplifier for the *Active Subwoofer* in this issue. All the remaining construction details will be in the final article next month.

In the meantime, if you're keen to commence construction of the *High-Performance Active Subwoofer*, you can gather all the parts in the parts list. You can then assemble the *Active Subwoofer* cabinet using the instructions in this article.

After that, you could assemble the *SC200* (or *Ultra-LD Mk.3/Mk.4*) *Amplifier Module* using the instructions in the January to March 2018 issues of *PE* (but without installing the output devices yet).

It would also be a good idea to build the *Four-Channel Speaker Protector* module (January 2023) but leave off one of the relays and the associated driving components. We only need to protect a single channel in this application.

Do not install the driver in the cabinet yet, although you can prepare to fit it. That's because you will need to install the acoustic wadding first (to be described next month). You will also need to connect a suitable length of heavy-duty speaker cable to the driver so that it can be connected to the yet-to-be-assembled amplifier module.

Next month, we'll have instructions for building the bracket that the amplifier sits on and that the mains power supply is also mounted on it. The amplifier module sits on one side of the bracket, with the *Speaker Protector* next to it. The transformer, bridge rectifier and capacitor bank mount on the other side, making for a compact integrated amplifier module.

On the rear of this module, outside the subwoofer cabinet, will be the amplifier heatsink, mains input socket, power switch and RCA signal input.

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Photo 9: I sanded and primed the active Subwoofer, then sanded it again and added a few filler touch-ups to make the joins perfectly smooth.

Photo 10: the Active Subwoofer with the final coat of 'rattle can' black paint. It's supposed to be satin but looks a lot like gloss.

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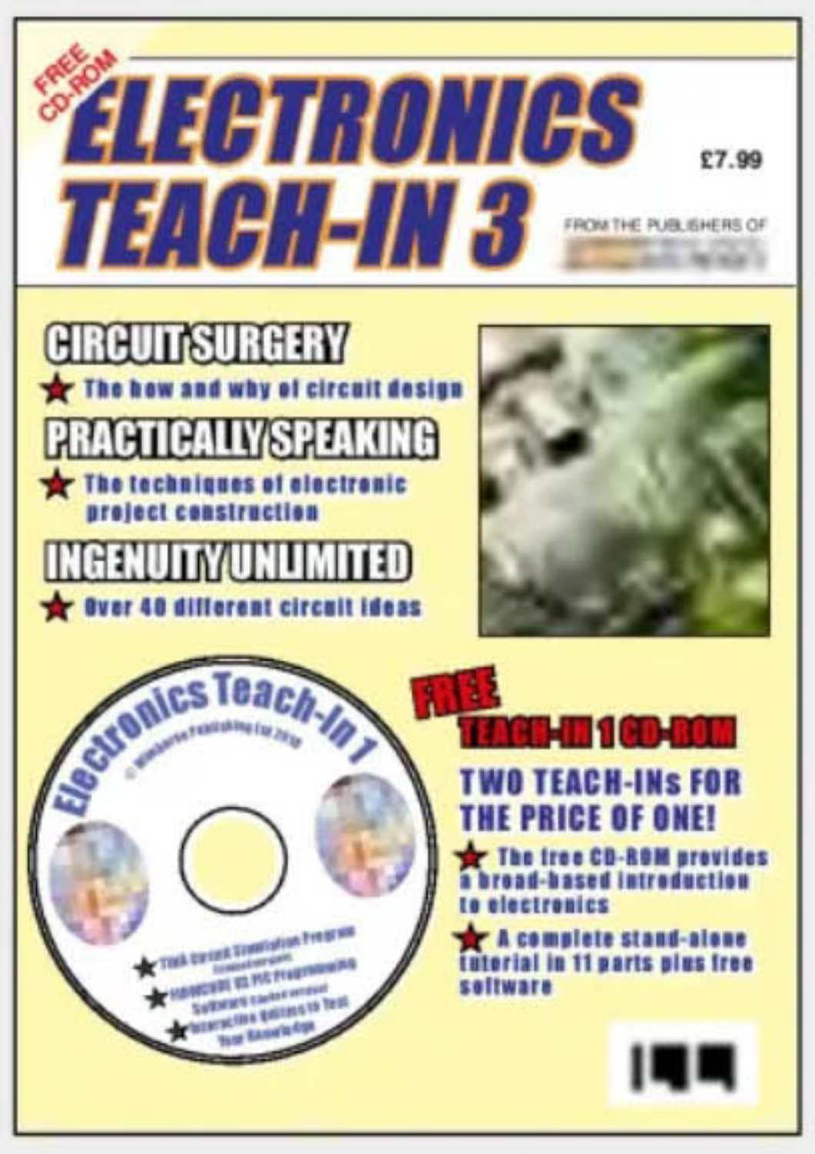
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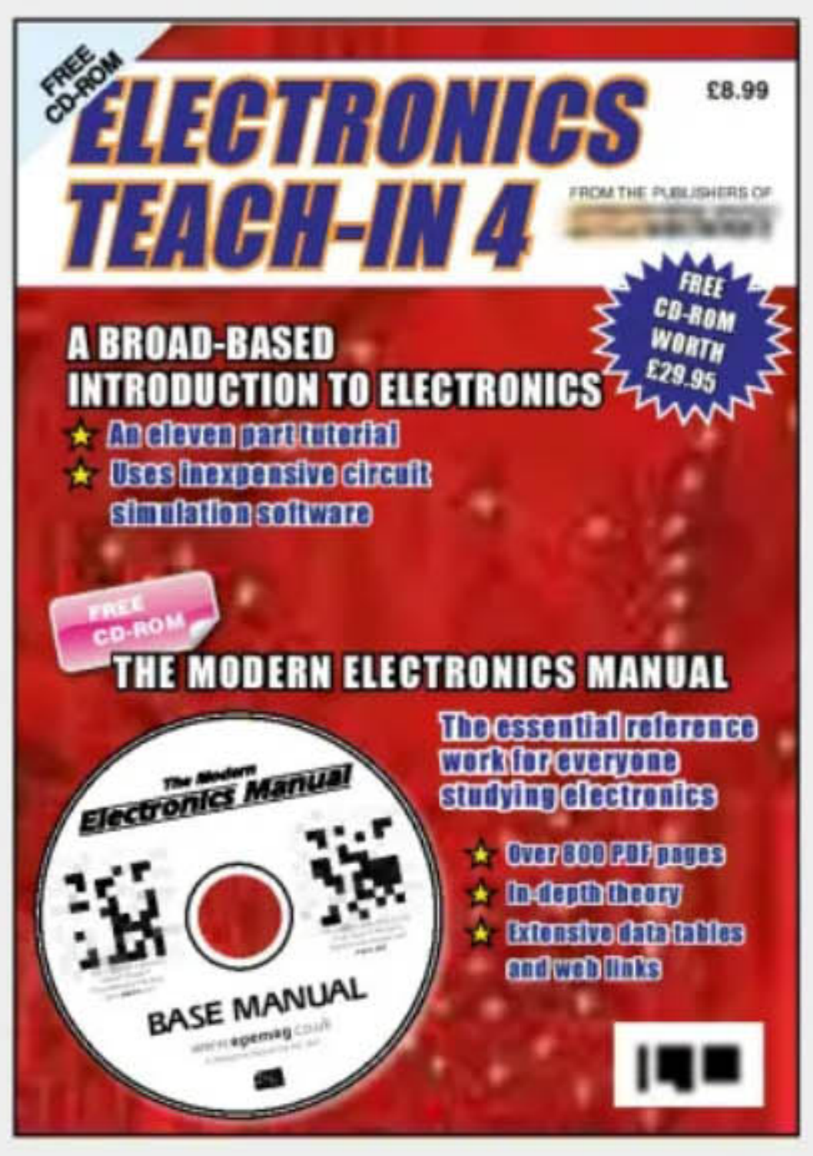
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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 13

WTW? ('What the What,' is my current favorite expression.) I can't believe it's practically 2024 already. I don't have a speech prepared and I don't have anything applicable to wear. What I do know is that we are poised to perform some exceedingly exciting experiments, so let's make sure we are all dressed appropriately. I'm thinking Monty Python Gumby attire (**https://bit.ly/3StpyHL**), which – by some strange quirk of fate – means I'm already ready to rock and roll.

But first…

I've received several emails from readers saying they remain confused by the concept of forward voltage drop in diodes in general, with light-emitting diodes (LEDs) forming a special case. As you may recall, we introduced this concept as part of calculating the value of an LED's current-limiting resistor in our first *Arduino Bootcamp* column (*PE*, January 2023).

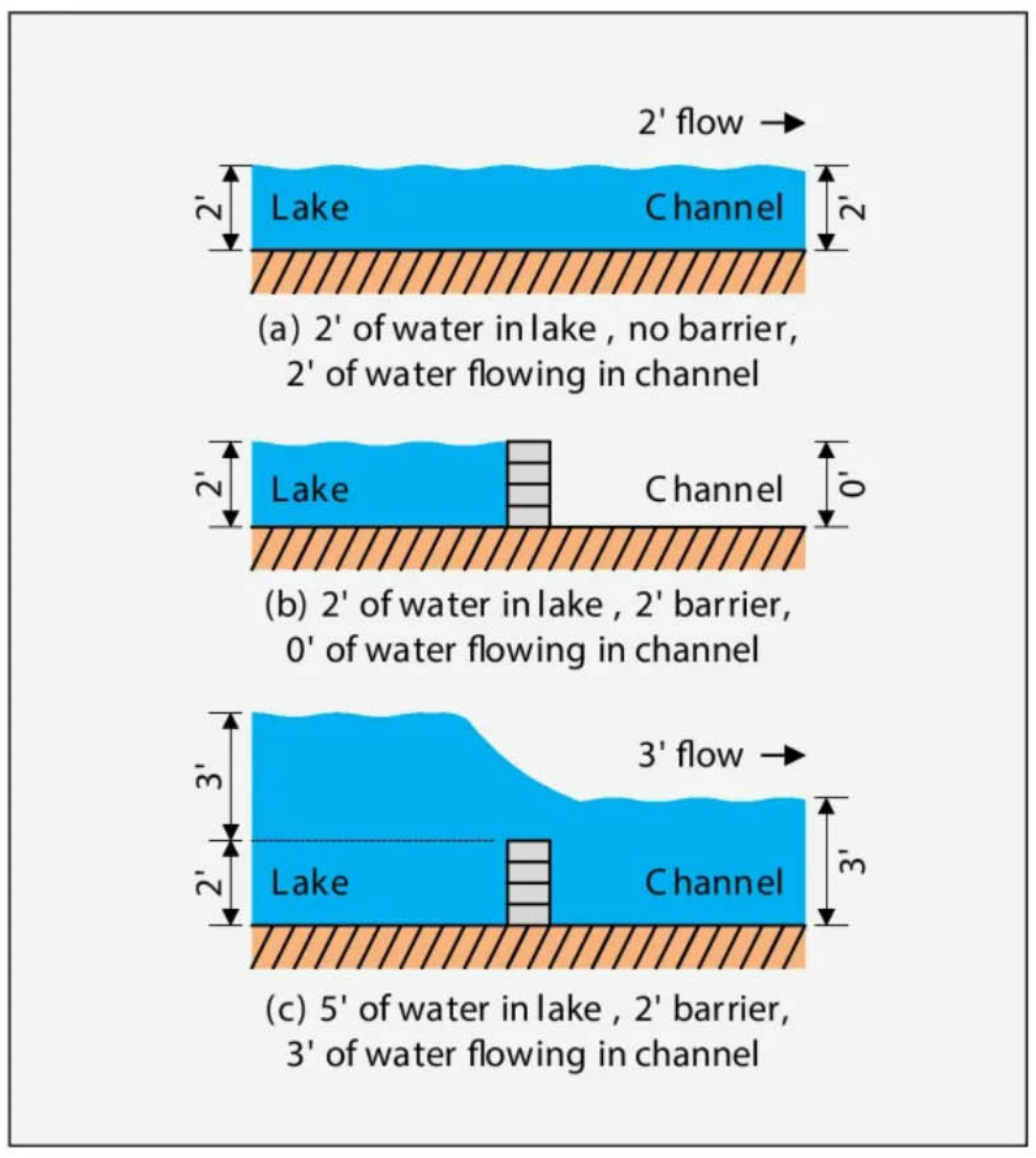
In our second *Bootcamp* column (*PE*, February 2023), we noted that the data sheet for the 7-segment display we're using stated that its LED segments had a forward voltage drop (aka V_F) of 2V and a maximum allowable forward current (I_F) of 20 milliamps (20mA), or 0.02A. As we are working with the Arduino Uno's 5V supply, and since we are working on the assumption that we want our segments to be as bright as possible, then using Ohm's Law $V = I \times R$ (which we can refactor as $R = V/I$) we calculated the value of our current-limiting resistors as $R = (5V – 2V) / 0.02A = 150\Omega$.

The question remains as to why we subtract V_F from our 5V supply. Although the equation is simple, the underlying mechanism is less than obvious to beginners (I know it confused the heck out of me). Well, the way a diode works, it doesn't start conducting until the potential difference across its input and output is greater than its forward voltage drop value. For any potential greater than this, we are currently assuming the LED acts like a simple piece of wire (apart from it emitting light, of course). The way I describe this if I'm giving a lecture is illustrated in Fig.1.

Imagine we have a lake, which represents our power source, feeding a channel, which represents a wire. The height of the water in the lake is equivalent to voltage, while any flowing water is equivalent to current. Fig.1a depicts a lake with 2 feet (yes, I'm an Imperial units chap here the US) of water (equivalent to 2V in our electrical circuit) and an unobstructed channel through which the water from the lake flows.

By comparison, in Fig.1b we introduce a 2-foot-high barrier, which represents our diode, across our channel, which represents our wire. In this case, assuming the water in the lake is only 2-feet deep, no water will flow through the channel.

Finally, in Fig.1c, we increase the depth of the water in the lake to 5 feet. Since the barrier is 2 feet tall, the result will be 3 feet of water flowing through the channel. I know analogies are always suspect, but I must admit to being rather proud of this one.



2' flow →
2'
Lake
Channel
2'
(a) 2' of water in lake, no barrier, 2' of water flowing in channel
2'
Lake
Channel
0'
(b) 2' of water in lake, 2' barrier, 0' of water flowing in channel
3' flow →
3'
2'
Lake
Channel
3'
(c) 5' of water in lake, 2' barrier, 3' of water flowing in channel

Fig.1. A graphical depiction of a diode's forward voltage drop.

There's more…

Transistors are semiconductor devices that can be used in various roles, including analogue amplifiers and digital switches. The two main classes of transistor with which we (well, you and I) typically come into contact are bipolar junction transistors (BJTs) and field-effect transistors (FETs). For the purposes of this column, we will be experimenting with a BJT.

We can dope pure, non-conducting silicon (add impurities into the crystal lattice) to form conducting N-type and P-type silicon. Any interfaces between these different flavours are where most of the magic occurs. BJTs come in two flavours, each with three doped regions ordered as NPN or PNP. The symbol for a generic NPN transistor is shown in Fig.2. Note the arrow pointing out of the heart of the transistor toward the emitter terminal. In the case of a PNP transistor symbol, this arrow would be pointing the other way. Two useful mnemonics are Not Pointing iN (NPN) and Pointing iN Proudly (PNP).

The origins of the terminal names (base, collector, and emitter) are too befuddling to go into here. Suffice it to say that the base acts as the control terminal. In the case of an NPN transistor wired as shown in Fig.2a, connecting the In signal to 0V will turn the transistor off (making it look like an open circuit or a break in the wire), in which case the Out signal will be pulled-up to 5V by the resistor. By comparison, connecting the In signal to 5V will turn the transistor on, thereby connecting the Out signal to 0V through the transistor.

When we consider the operation of this simple circuit (Fig.2b), we see that the transistor is acting as an inverter; that is, the Out signal has the opposite value to the In signal.

What's not obvious from Fig.2 is that only a small amount of current needs to be applied to the base (known as the base current, I_B). This small current is amplified into a much larger current flowing between the collector and the emitter (this is known as the collector current,

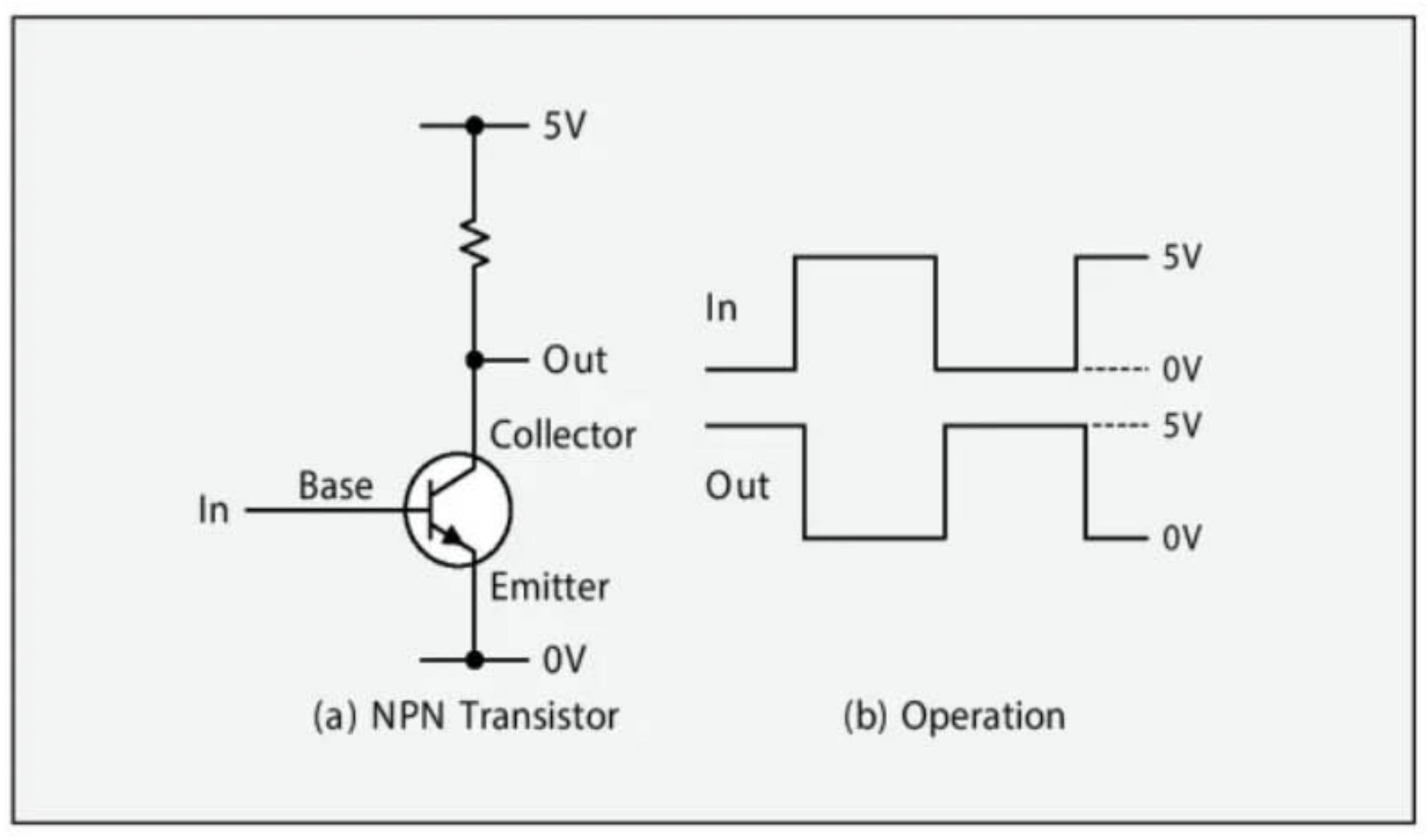
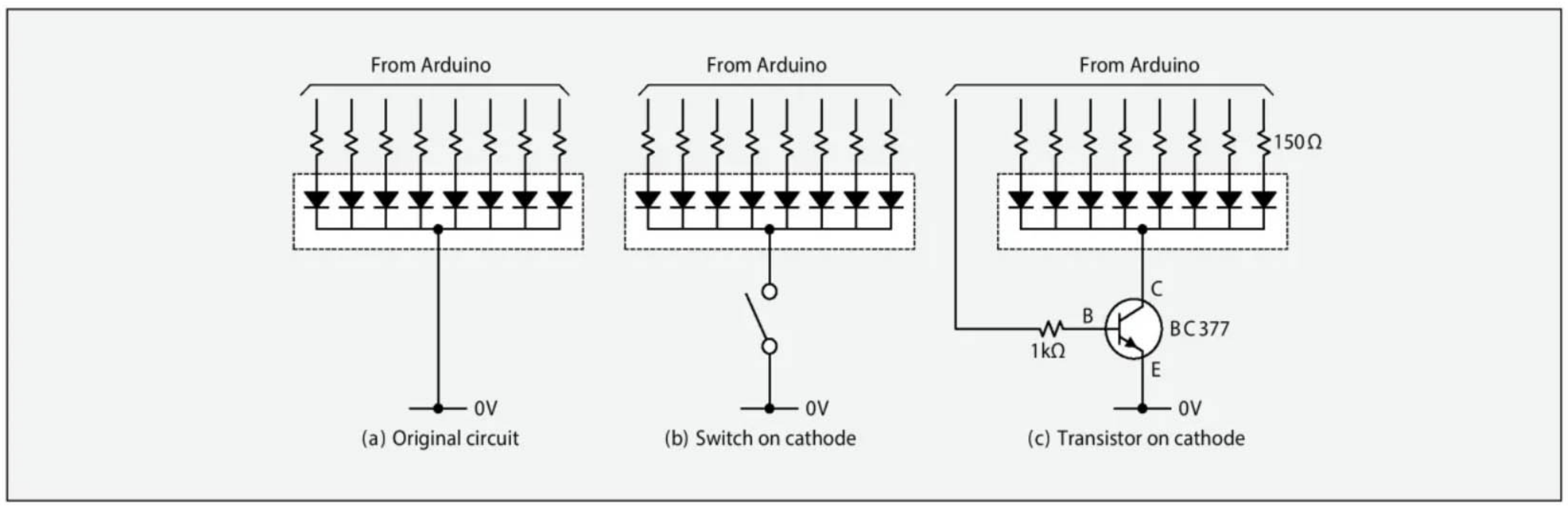


Fig.2. A generic NPN transistor.



(a) Original circuit

(b) Switch on cathode

(c) Transistor on cathode

Fig.3. Controlling all the segments together.

I_C). I don't want to give too much away here, but suppose we wished to control all eight* LEDs on our 7-segment display with a single pin on our Arduino (*in addition to the 7 main segments, there's also a DP (decimal point) segment). Since each segment has a maximum current of 20mA, we would be talking about 8 × 20mA = 160mA. Unfortunately, the digital pins on an Arduino Uno have a maximum current limit of only 40mA, and they really shouldn't be asked to handle more than 20mA for extended periods of time.

Happily, we can easily find a transistor that can handle an I_C current of 160mA between its collector and emitter terminals, and we can control such a transistor by applying a much smaller current – one the Arduino can easily supply – to the transistor's base.

That's all we need to know to set the stage for the wonders that are to come. If you wish to learn more about fundamental BJT and FET concepts, may I make so bold as to recommend my book, *Bebop to the Boolean Boogie: An Unconventional Guide to Electronics* – see: **https://bit.ly/3u9XIWV**

Semiconductor switcheroo

We introduced the concept of light-dependent resistors (LDRs) in our previous column (*PE*, December 2023). We finished that column by employing our Arduino to read values from an LDR and display those values on the Serial Monitor. If you wish, you can refresh your memory by downloading a copy of this program (file **CB-Jan24-01.txt**). As usual, all the files mentioned in this column are available from the January 2024 page of the *PE* website (**https://bit.ly/pe-downloads**).

If you've been following this series, you will be more than familiar with our existing breadboard layout, which – at its heart – has our single-digit common cathode 7-segment display along with eight 150Ω current-limiting resistors (one per segment). However, if you're new to the party, you might wish to download an image of our current breadboard layout showing our LDR, trimpot, piezoelectric buzzer and 7-segment display – along with various pull-up and current-limiting resistors – coupled with the connections to our Arduino Uno (file **CB-Jan24-02.pdf**).

What we want to do now is use the value from an LDR to control the brightness of our 7-segment display. We're going to keep this simple. In low-light conditions (which we will start off by defining as any LDR reading less than 200), we will assume it's night time and we will dim our display to a fraction of its full brightness. For any higher ambient light level (an LDR reading of 200+), we will drive our display as brightly as we can.

Until now, the way we've been controlling the LEDs on our 7-segment display is as illustrated in Fig.3a. In this case, the anode of each LED is controlled by its own digital pin on the Arduino (since we're using a common-cathode display, all the LEDs' cathodes are connected and presented as one).

In our last-but-one column (*PE*, November 2023), we noted that Arduinos include special hardware implementations of pulse-width modulation (PWM) functions associated with some of their digital pins. In the case of the Arduino Uno, there are six such pins (3, 5, 6, 9, 10, 11), indicated by '~' characters on the board.

The Arduino doesn't have true analogue outputs but – as discussed in an earlier column (*PE*, March 2023) – the PWMs provide a pseudo-analogue capability. We access the PWMs using calls to the Arduino's built-in `analogWrite()` function, which accepts two arguments – the pin we wish to control and a value between 0 and 255.

One of the PWM-equipped pins (pin 6) drives segment D on our 7-segment display. The way we've wired our circuit, a PWM value of 0 on Pin 6 will turn that segment fully off (0% brightness), a value of 255 will turn it fully on (100% brightness), and in-between values will result in a corresponding brightness (128 will result in 50% brightness, for example). We experimented with this in *PE*, November 2023.

Let's suppose we now wish to control the brightness of all the segments on the display using PWM functionality. There are two problems with our current approach. First, we have eight segments on the display but only 6 PWM-equipped pins on the Arduino. Second, it would be painful (figuratively speaking) for us to be obliged to specify the brightness values of the segments individually.

What we want is a way to control the brightness of all the segments simultaneously. The only pin that's shared by all the LEDs is the display's common cathode. Suppose we added a hand-controlled switch (Fig.3b). Now, we can turn the segments on and off *individually* using the Arduino's pins, and we can turn them on and off *collectively* using our switch.

If we could repeatedly turn our switch on and off quickly enough, thereby implementing a clunky PWM function, we could control the brightness of all *active* segments simultaneously. The solution is to replace our switch with a transistor and to control that transistor using one of the Arduino's PWM-equipped pins (Fig.3c). (Yes, a 'Tra-la' is certainly in order.)

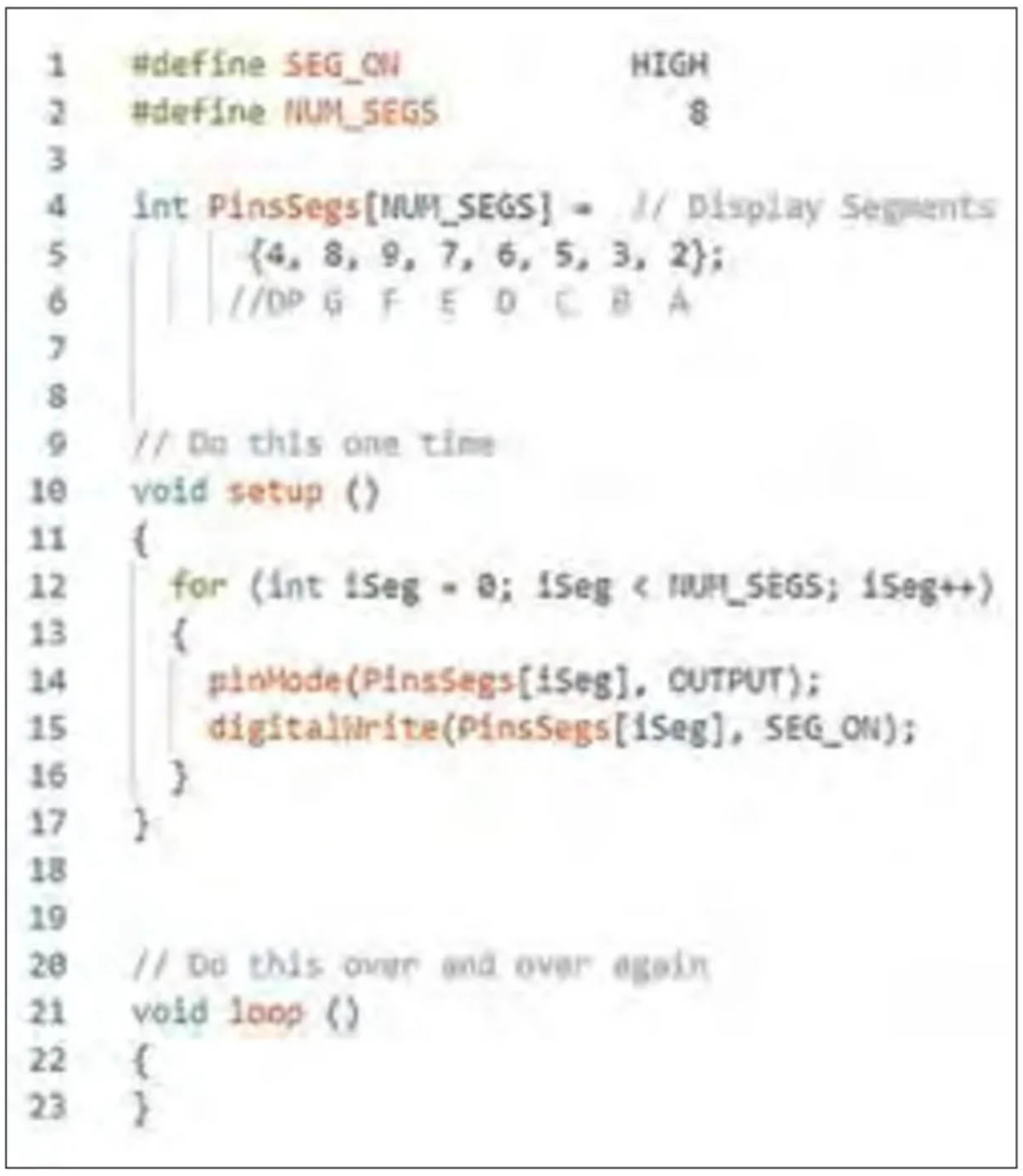
Which transistor?

This is where things start to get interesting. When turned on, NPN transistors have their own voltage drop. As a rule of thumb, we typically assume this to be 0.7V. Returning to Fig.1c, this is like adding an extra 0.7 feet to our existing 2-foot barrier, resulting in 5 – 2.7 = 2.3 feet of water flowing through the channel. Suppose we stick with our existing 150Ω current-limiting resistors. Returning to Ohm's law $V = I \times R$, we now know V and R, so refactoring the equation to be $I = V/R$ gives us $I = (5 - 2.7) / 150 =$ ~15mA. This means that if all eight segments are fully on, we will have a total current of 8 × 15mA = 120mA.

If we were desperate to achieve the maximum possible brightness, which – as we know – corresponds to an I_F of 20mA, we could recalculate the values of our current-limiting resistors using $R = V/I$, which gives us $R = (5V - 2.7V) / 0.02A = 115Ω$. Since the closest standard resistor values are 110Ω and 120Ω, we would opt for the higher value of 120Ω, resulting in a slightly lower current of $I = (5 - 2.7) / 120 =$ ~19mA, which is 'close enough for government work,' as they say.

Are you desperate enough to replace all your 150Ω current-limiting resistors with their 120Ω counterparts? If so, go for it. For myself, I'm going to stick with what we've got (for the moment, at least).

The internet is a wonderful resource, but it's not without its problems. For example, if you perform a Google search for something like 'Controlling the brightness of a common-cathode 7-segment display with a transistor,' you may run across circuits showing BC547 NPN transistors (for example, **https://bit.ly/49zpYTa**). Rather than blindly



```
1   #define SEG_ON            HIGH
2   #define NUM_SEGS             8
3
4   int PinsSegs[NUM_SEGS] =   // Display Segments
5         {4, 8, 9, 7, 6, 5, 3, 2};
6         //DP G  F  E  D  C  B  A
7
8
9   // Do this one time
10  void setup ()
11  {
12    for (int iSeg = 0; iSeg < NUM_SEGS; iSeg++)
13    {
14      pinMode(PinsSegs[iSeg], OUTPUT);
15      digitalWrite(PinsSegs[iSeg], SEG_ON);
16    }
17  }
18
19
20  // Do this over and over again
21  void loop ()
22  {
23  }
```

Listing 3a. Light up all the segments.

follow someone else's circuit, this is the point when you should say to yourself, 'Let me check the data sheet first' at: **https://bit.ly/479vs5p**

It doesn't take long to discover that the BC547 has a maximum I_C of only 0.1A, or 100mA, which isn't sufficient to handle the 120mA associated with our existing 150Ω current-limiting resistors, let alone the 8 x 19mA = 152mA we would see if we decided to use 120Ω current-limiting resistors.

There are two solutions, if we were on a mission-critical assignment to save the world (I've been watching too many science fiction films) and all we had at our disposal was a single BC547 transistor that we were determined to use, then we could say that our maximum I_C of 100mA equates to 100mA/8 segments = 12.5mA per segment. Using this new intelligence, we could recalculate our current-limiting resistors as R = (5V – 2.7V) / 0.0125A = 184Ω. In this case, the closest standard resistor values are 180Ω and 200Ω, and we would opt for the latter to be on the safe side.

However, since we aren't tasked with saving the world, and as we aren't pushed for time, a better alternative is to select a transistor capable of meeting our requirements, such as the BC377, for example. Checking its datasheet, we see this little scamp has a maximum I_C of 1A, which is more than sufficient to meet our current (no pun intended) and future needs – see: **https://bit.ly/3QCc3mo**

We will be requiring only one BC377 in this column, but we will be using two or three in future experiments, so I'd get at least five ('just because'). You can obtain these little rascals from any component supplier, but I just found an awesome deal on Amazon for a variety of 20 each of ten types of NPN and PNP transistors (including BC377s), which means a total of 200 transistors, all for only £6.99: **https://bit.ly/40xAgyS**

This is mind-boggling when you think that this would have been the price of a single transistor circa 1960.

One step at a time

If I've taught you anything in this series, I hope it includes taking things one step at a time. This is because it's a lot easier to verify and debug things in isolation than it is to tackle a bunch of things all at once. So, before we add our transistor into the mix, let's start by creating a simple program whose task is to light all the segments on the display, including the decimal point (Listing 3a, file **CB-Jan24-03.txt**). (Remember that, following some confusion in earlier columns, we're now using a scheme in which **the listing num**ber [Listing 3 in this example] corresponds to the associated program file [**CB-Jan24-03.txt** in this example], after which we use 'a', 'b', 'c'… suffixes as appropriate.)

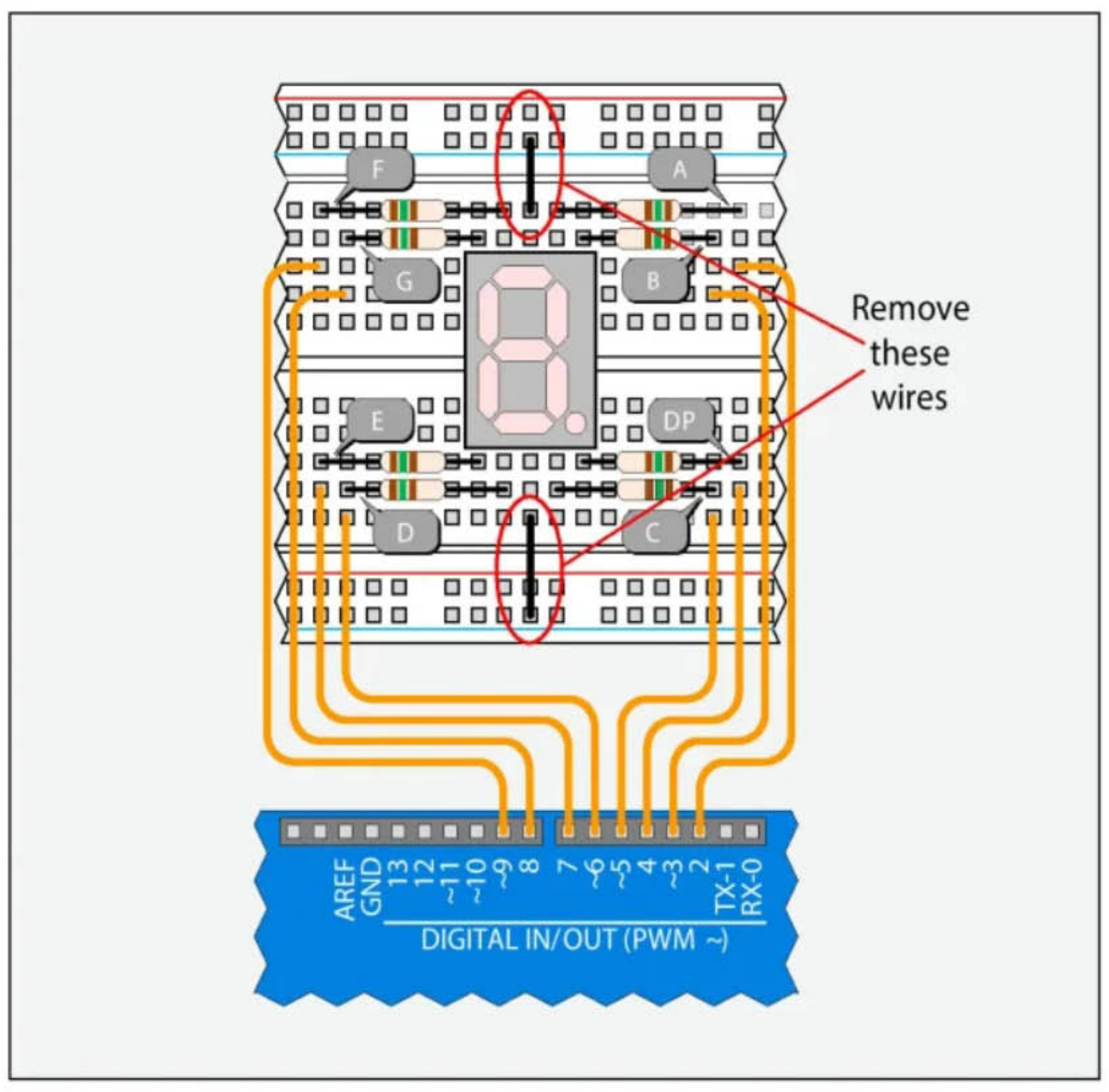


Fig.4. Removing the two GND wires.

There's nothing here we haven't seen before. On Lines 4 and 5, we declare an array of integers `PinsSegs[]`, which we initialise with the numbers of the Arduino pins that are driving the LEDs in our 7-segment display. On Lines 12 through 16 in our `setup()` function, we use a `for()` loop to cycle through each pin in turn, first defining it as being an `OUTPUT`, and then assigning it a value of `SEG_ON`, which will light that segment up. Once all of the segments have been illuminated, the `loop()` function just cycles round doing nothing.

I just ran this program. All my LEDs are glowing furiously, which means we're now ready to turn our attention to the transistor itself (imagine a roll of drums if you will) ...

Adding the transistor

Before we add the BC377 transistor to our breadboard, we first need to make some changes. Specifically, we need to remove the two black ground (GND) wires shown in Fig.4.

Why two GND wires? Isn't that a little enthusiastic? Well, as we discussed when we first established our breadboard (*PE*, February 2023), the display we are using has two pins (3 and 8) that are connected inside the device to form the common cathode. We could have connected either of these to the GND (0V) rails on our breadboard. The reason we connected both is to provide redundancy. If one of our black jumper leads is bad (broken inside), for example, then the other will suffice. As we also discussed, although we don't need both connections in this instance, we would use both if we were creating a safety-critical or mission-critical system 'just in case,' and this is a good mindset to adopt.

The BC377 transistor we are using is presented in a TO-92 plastic package (Fig.5). The pin numbers are associated with the package, which means they're always the same in relation to the package's 'D' shape. However, the association between the pin numbers and the collector, base and emitter signals can vary on a transistor-type-by-transistor-type basis, so be careful and *always* check the data sheet! Let's add this transistor to our breadboard, along with associated wires, as illustrated in Fig.6.

If we compare Fig.6 to Fig.3c, we see that the green wire connects the collector (pin1) on the transistor to pin 3 on the 7-segment display. The black wire

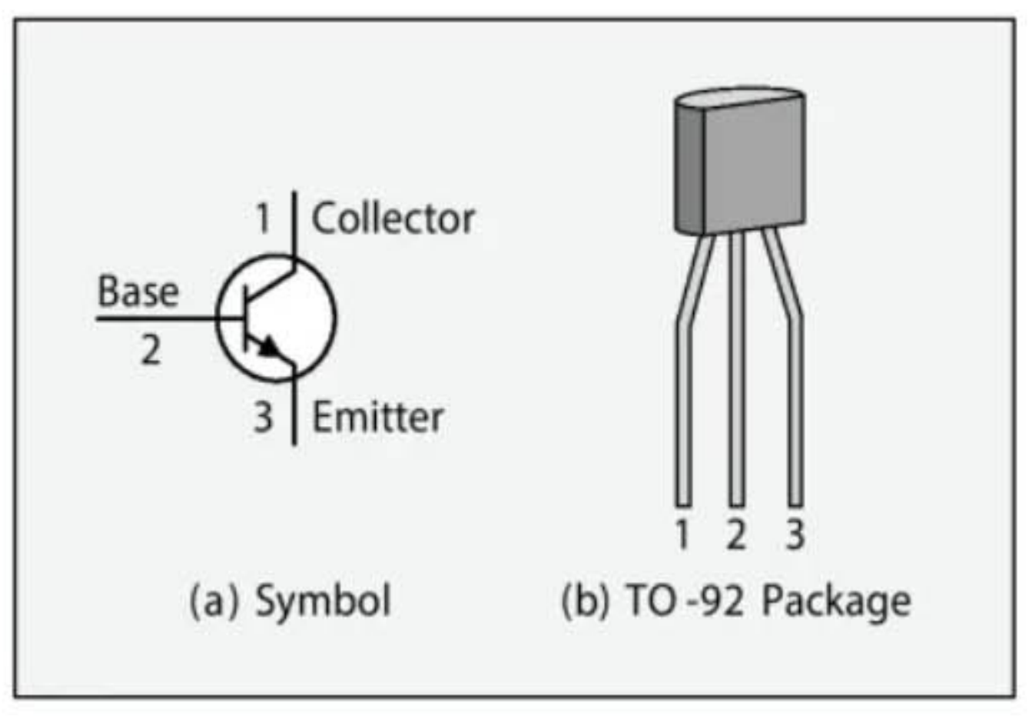


Fig.5. BC377 symbol and plastic D-shaped package.

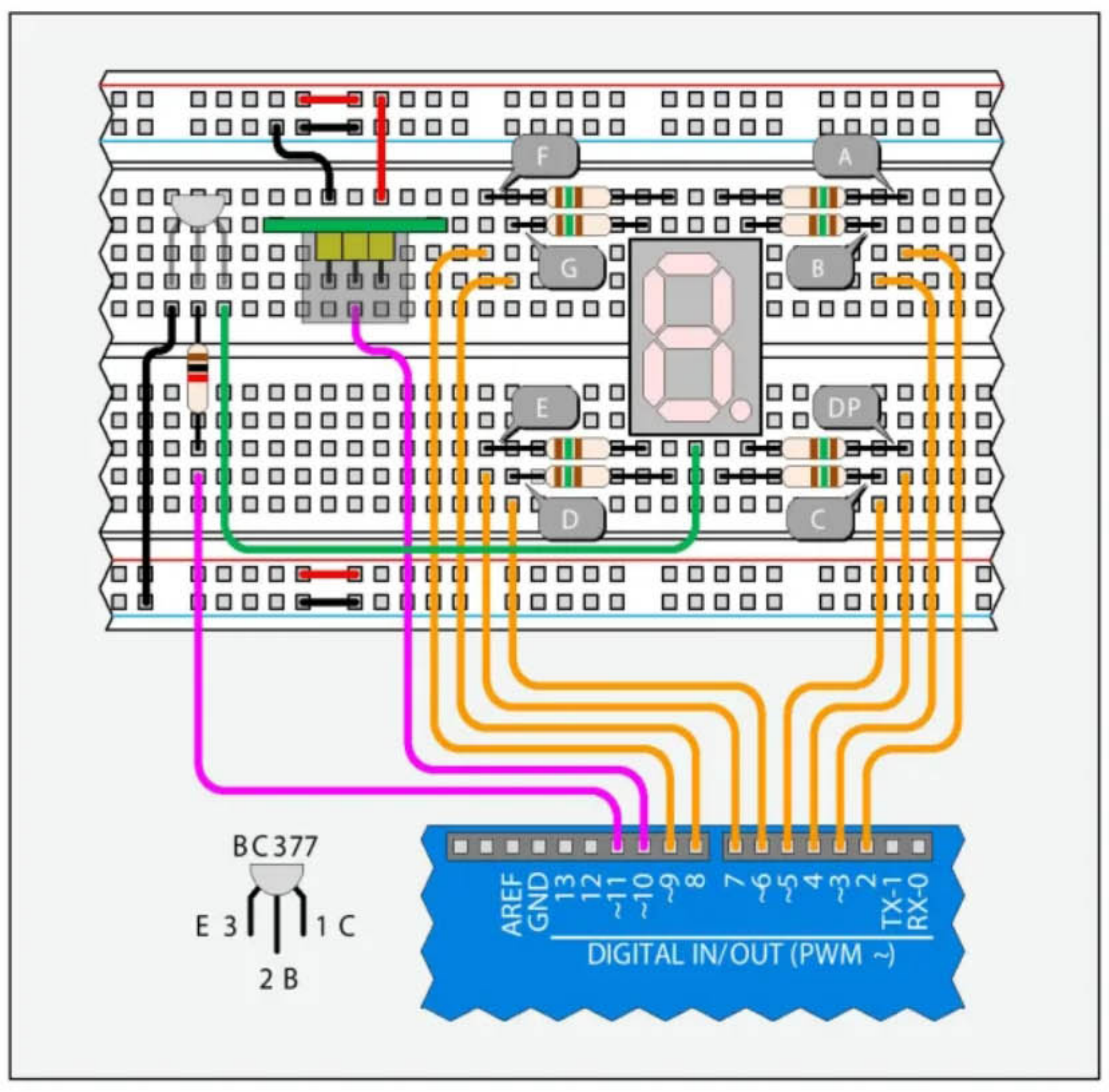


Fig.6. Adding the BC377 transistor.

connects the emitter (pin 3) on the transistor to the GND (0V) rail. And the base (pin 2) on the transistor is connected to one side of a 1kΩ (brown, black, red) resistor, the other side of which is connected to pin 11 on the Arduino using a purple wire. As denoted by the '~' character on the Arduino's board, this pin is equipped with a hardware PWM function inside the Arduino.

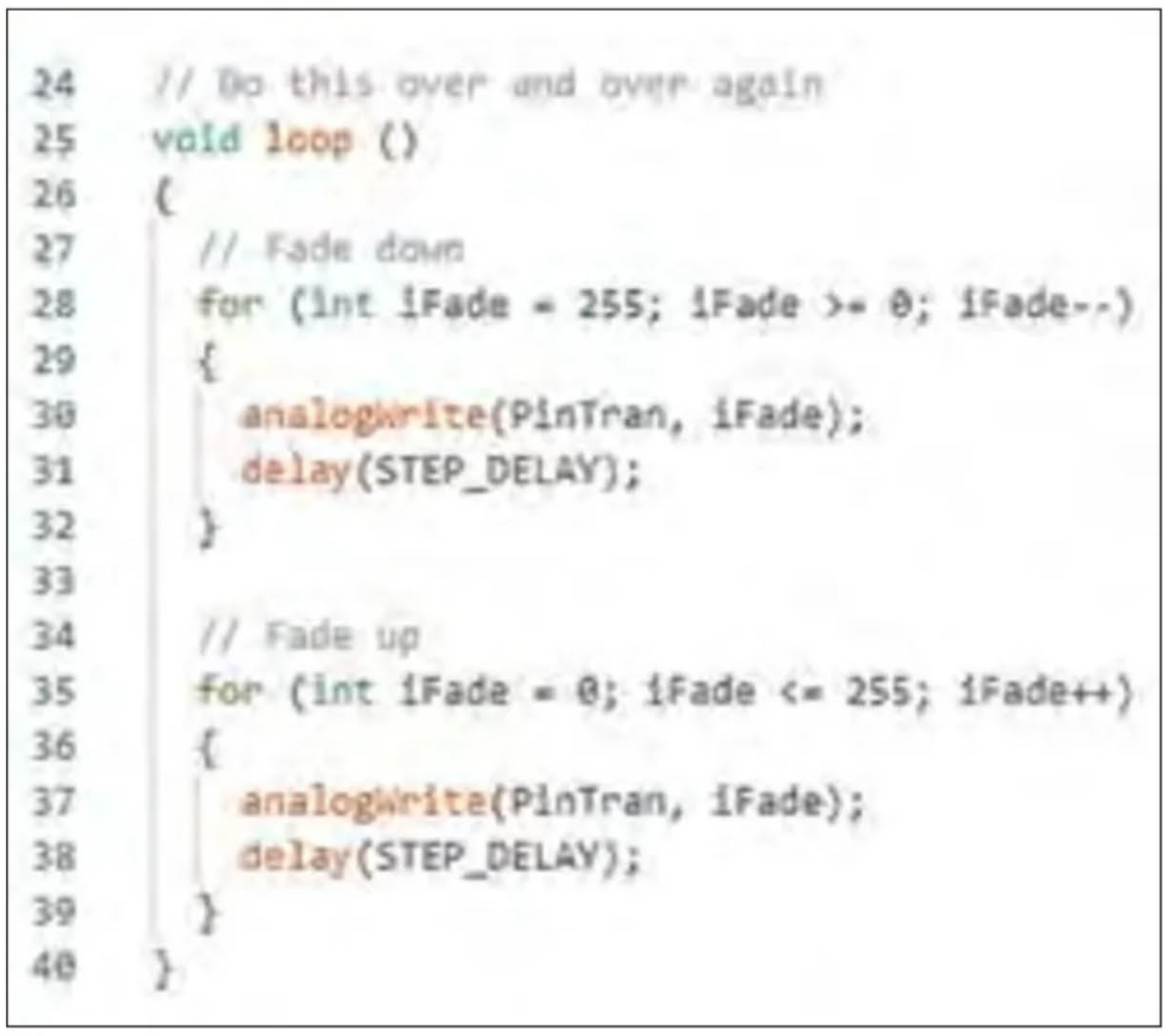
An image of our full breadboard layout – including the BC377 – is available for your perusing pleasure (file **CB-Jan24-04.pdf**).

OK, let's modify our current test program to cause all the segments on the display to cycle around gradually brightening and dimming. We'll start by adding a new definition, `STEP_DELAY`, which we will use to control the speed with which the display brightens and dims. We'll also declare an integer `PinTran` to which we will assign the number of the Arduino pin (pin 11) that we are using to drive the base of our transistor (via the 1kΩ resistor).

The `setup()` function turning all the segments on individually will remain unchanged. The main modification will be to the `loop()` function, as illustrated in Listing 5a (file **CB-Jan24-05.txt**).

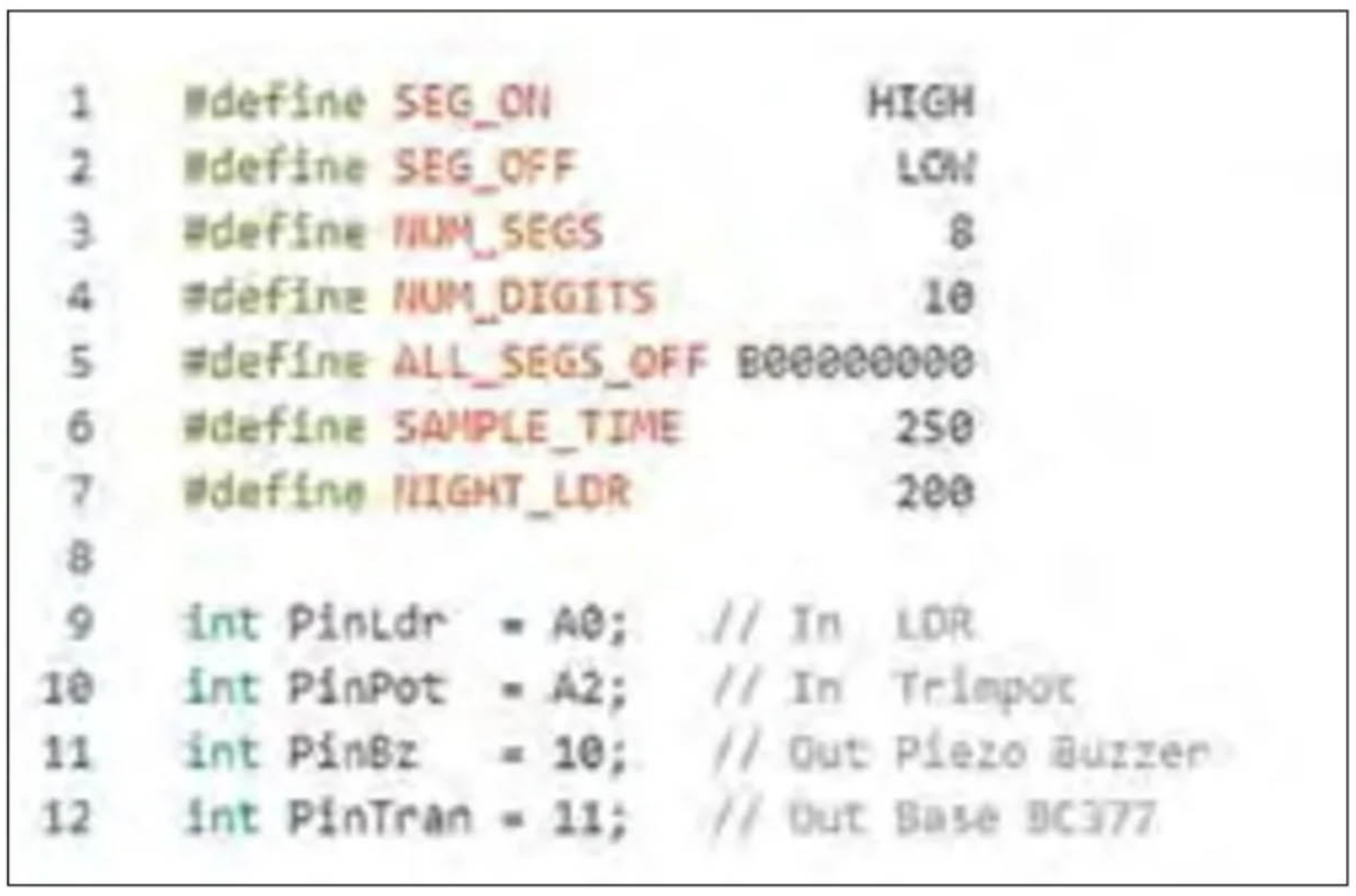
Since all the segments have been lit up by the `setup()` function, we commence the `loop()` function by fading everything down using the `for()` loop on Lines 28 to 32, after which we fade everything back up again using the `for()` loop on Lines 35 to 39.

To be honest, wrapping our brains around how this works requires some mental gymnastics. We know that we've used the `setup()` function to apply `HIGH` (5V) to all the segment anodes to turn the LEDs on. We also know that if we apply the same electrical potential (eg, 5V) to both sides of an LED, then it won't conduct, so why do we start our `for()` loop on Line 28 with a value of 255, which equates to 5V on the Arduino's pin?



```
24  // Do this over and over again
25  void loop ()
26  {
27    // Fade down
28    for (int iFade = 255; iFade >= 0; iFade--)
29    {
30      analogWrite(PinTran, iFade);
31      delay(STEP_DELAY);
32    }
33
34    // Fade up
35    for (int iFade = 0; iFade <= 255; iFade++)
36    {
37      analogWrite(PinTran, iFade);
38      delay(STEP_DELAY);
39    }
40  }
```

Listing 5a. Using the transistor to control the brightness.



```
#define SEG_ON              HIGH
#define SEG_OFF              LOW
#define NUM_SEGS               8
#define NUM_DIGITS            10
#define ALL_SEGS_OFF B00000000
#define SAMPLE_TIME          250
#define NIGHT_LDR            200

int PinLdr  = A0;   // In  LDR
int PinPot  = A2;   // In  Trimpot
int PinBz   = 10;   // Out Piezo Buzzer
int PinTran = 11;   // Out Base BC377
```

Listing 6a. Definitions and pin assignments.

Allow me to refer you back to Fig.2 and remind you that our transistor acts as an inverter. This means that when we use the Arduino to drive 255 (5V) onto the base of our BC377 transistor at the start of our `for()` loop on Line 28, this turns the transistor on, which connects the common-cathode pin on the 7-segment display to GND, thereby activating all of the segments. Similarly, when we use the Arduino to drive 0 (0V) onto the base of the transistor at the end of our `for()` loop on Line 28, this turns the transistor off, which prevents it from conducting, thereby deactivating all of the segments.

Upping the ante

Just for giggles and grins, I've combined a couple of our earlier programs together. I started with the program we created last month (*PE*, December 2023) that reads the value from the trimpot, maps it into a range of 0 to 9, presents this value on our 7-segment display, and plays a musical note corresponding to that number using our piezoelectric buzzer.

I also took parts of the program from last month that reads the value of the LDR, along with parts of the program from this month that uses our transistor to control the brightness of the display.

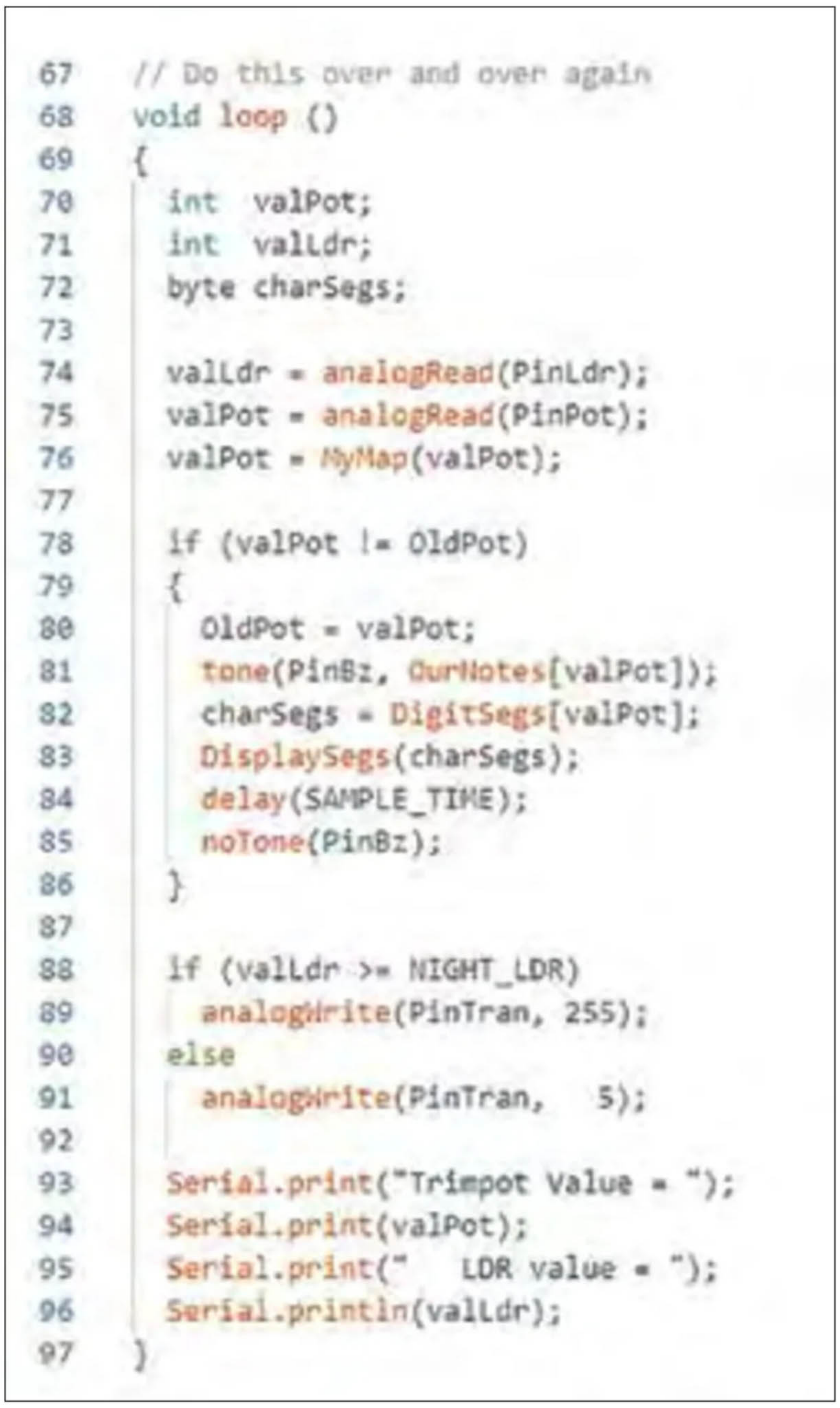
I munged all this together to form a new super-duper program that reads the value from the trimpot, maps it into a range of 0 to 9, presents this value on the 7-segment display, plays a musical note, and reads the value from the LDR. If the value on the LDR is >=200 (greater than or equal to 200), then the value on the 7-segment display is presented at full brightness, otherwise it's dimmed to a fraction of its full value.

You can peruse and ponder this program at your leisure (file **CB-Jan24-06.txt**). All we need to do at the moment is look at the definitions and pin assignments (apart from the pins driving the segments), as seen in Listing 6a, along with the main `loop()` function, as shown in Listing 6b.

You'll see we've moved things around a bit in the `loop()` function, but it's still fundamentally similar to what we've seen before. We use the `if()` test on Line 78 to see if our trimpot has changed. If so, we present the new value on our 7-segment display and we play a tone on our piezo buzzer.

We now perform a new `if()` test on Line 88. If the value read from our LDR is >= `NIGHT_LDR` (which we've tentatively defined as 200), then we use the transistor to drive the display at its full brightness, otherwise, we drive it at a fraction of this value.

We're still using serial commands on Lines 93 to 96 to display the mapped values from the trimpot, along with the



```
// Do this over and over again
void loop ()
{
  int  valPot;
  int  valLdr;
  byte charSegs;

  valLdr = analogRead(PinLdr);
  valPot = analogRead(PinPot);
  valPot = MyMap(valPot);

  if (valPot != OldPot)
  {
    OldPot = valPot;
    tone(PinBz, OurNotes[valPot]);
    charSegs = DigitSegs[valPot];
    DisplaySegs(charSegs);
    delay(SAMPLE_TIME);
    noTone(PinBz);
  }

  if (valLdr >= NIGHT_LDR)
    analogWrite(PinTran, 255);
  else
    analogWrite(PinTran,   5);

  Serial.print("Trimpot Value = ");
  Serial.print(valPot);
  Serial.print("   LDR value = ");
  Serial.println(valLdr);
}
```

Listing 6b. The main `loop()`

values read from the LDR, on the Serial Monitor to help us to work out what's happening.

For example, I started off with my LDR exposed to room-level light, which resulted in my 7-segment display operating at full brightness as expected. However, when I put my finger over the LDR, the 7-segment display continued to operate at full brightness. Looking at the Serial Monitor revealed that although the value from the LDR had fallen, it was still higher than the 200 threshold I'd set. The problem is that light seeps in through the sides of the LDR as well as through its face. Shrouding the LDR with a small piece of cardboard caused its value to fall below 200, at which time the 7-segment display dimmed accordingly (hurrah!).

If we were using this technique to control a bedside clock, for example, then we would perform some real-world experiments to determine the ideal threshold value. We might also provide some way for the user to modify the threshold value, but that's a story for another day.

Components from Part 1	
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk
Components from Part 2	
7-segment display(s)	https://amzn.to/3Afm8yu
Components from Part 5	
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Components from Part 6	
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX
Components for Part 9	
SW-18010P vibration switch	https://bit.ly/46SfDA4
Components for Part 10	
Breadboard mounting trimpots	https://bit.ly/3QAuz04
Components for Part 12	
Light-Dependent Resistor	https://bit.ly/3S2430m
Components for Part 13	
BC337 NPN Transistor	https://bit.ly/40xAgyS

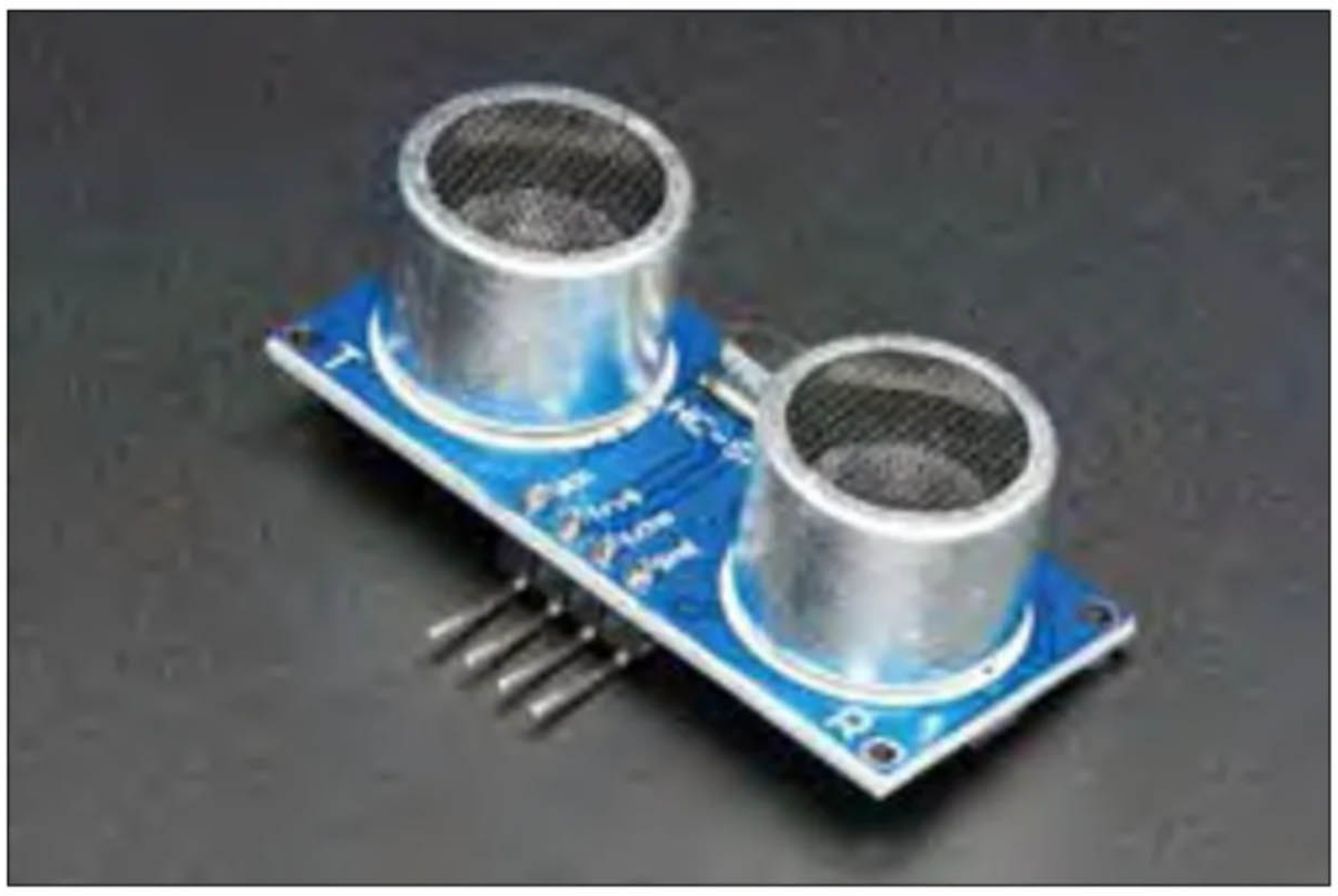


Fig.7. The HC-SR04 ultrasonic sensor (Source: Adafruit)

That's batty!

The hearing ability of a healthy young human typically spans 20Hz to 20,000Hz (20kHz). Frequencies below 20Hz are classed as 'infrasound.' Although barely perceptible to humans, various animals – including elephants, hippopotamuses and whales – communicate via infrasonic means. Frequencies above 20kHz are classed as 'ultrasound.' Some animals – like dolphins, frogs and tarsiers – communicate using ultrasonic sounds; others, like bats, use ultrasound for echolocation purposes.

Have you ever seen bats flying at night? Their ability to use ultrasonic echolocation to navigate through complex three-dimensional terrains while identifying and homing in on prey like moths and mosquitoes is nothing short of phenomenal. It's so phenomenal that a huge chunk of their little batty brains is devoted to hearing.

As Groucho Marx famously said, 'From the moment I picked your book up until I laid it down, I was convulsed with laughter. Someday I intend reading it.' The reason I mention this here is that there's a legendary paper on the topic of consciousness by American philosopher Thomas Nagel titled, *What Is It Like to Be a Bat?* – someday I intend reading it – see: **https://bit.ly/3SyGmgz**

In the meantime, humans have developed technologies that allow is to use ultrasonic sound for things like object detection and distance measurement. For example, there's the

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

well-known HC-SR04 ultrasonic sensor (Fig.7). This little beauty is available from multiple suppliers, including Adafruit via Amazon: **https://bit.ly/49AMBq4**

Next time

I can barely control my excitement, because we are going to do all sorts of cool things in our next column. We will commence by employing an HC-SR04 ultrasonic sensor to measure distances, present the results on our 7-segment display, and implement a soon-to-be fabled therabone, which will be our 21st Century answer to the 20th Century's theremin: **https://bit.ly/3ubLrBj**

Next, while the haunting sound of the therabone still echoes in our ears (and tears of joy still roll down our cheeks), we are going to introduce the concept of real-time clocks (RTCs). In addition to using an RTC to keep track of the time, we will also display the result on… you guessed it… our 7-segment display. This will be the first step along our path to creating a suite of 1-digit, 2-digit, and 4-digit clocks. Until then, as always, I'm only an email away.

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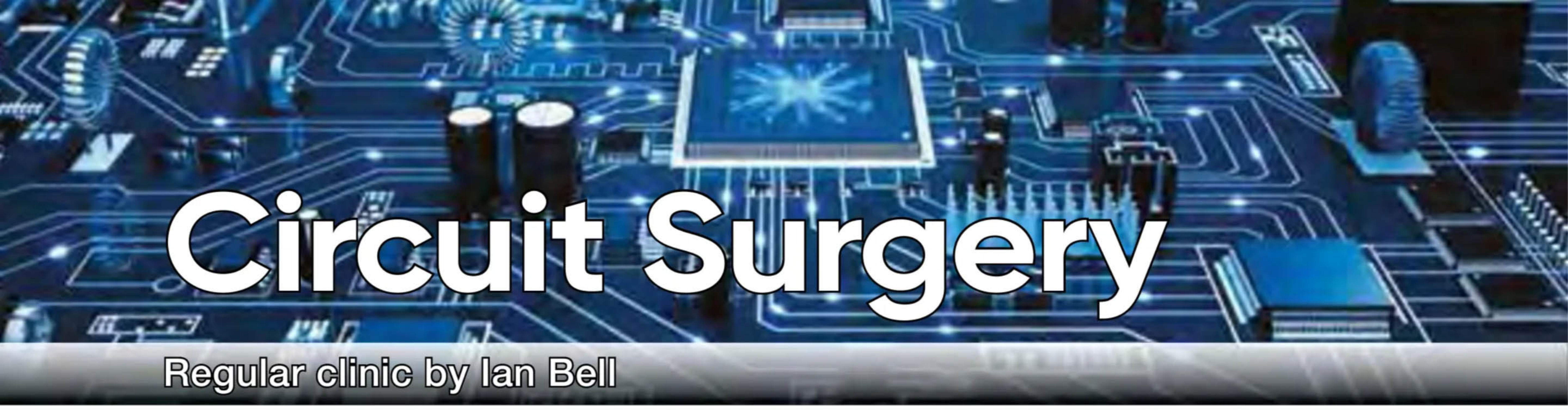


Circuit Surgery

Regular clinic by Ian Bell

Frequency shifting and superheterodyne receivers – Part 2

Last month, we started looking at superheterodyne radio receivers, mainly concentrating on the principles of heterodyning (frequency shifting) and the mixers that provide this function. This month, we will look at the structure and operation of superheterodyne radio receivers in more detail.

Radio transmission systems are fundamentally based on heterodyning. The signal to be transmitted, referred to as the message signal, (for example, speech) is upshifted from its original frequency range (called the baseband) to the much higher frequencies (radio frequencies – RF) required for practical wireless transmission of electromagnetic signals. This is achieved by varying (modulating) one or more properties of an RF carrier signal in sympathy with the message signal. A radio receiver must then downshift the signal from the RF carrier frequency to the original baseband to recover the message, which is referred to as demodulation or detection.

Mixer recap

The principle of the superheterodyne receiver is downconversion to a fixed intermediate frequency (IF) before further downcoversion to the baseband. The intermediate frequency used in superheterodyne receivers is at a much higher frequency than audio (hence the 'super' part of the name). The fact that the IF is a fixed frequency makes the design of a receiver with good performance much easier than if most of the circuitry has to cope with (be tuneable to) the full range of carrier frequencies which need to be received.

Heterodyning is achieved using mixers. These are nonlinear circuits that combine signals to produce new frequencies (heterodynes) not present in the input. We discussed mixers in detail last month. To recap briefly, an ideal mixer multiplies two signals, but if signals are combined (added) and applied to any nonlinear circuit then heterodyning will occur. With two input frequencies (two sinusoid inputs) multipliers output just the sum and difference frequencies, whereas with other nonlinear circuits there may also be many other output frequencies. We often only want one of the sum or difference frequencies, so we have to filter the mixer output to remove the unwanted signals. Multiplier circuits require a relatively large number of transistors to implement so are more commonly found on integrated circuit receivers. The nonlinearity of a single transistor or diode (or tube/valve in the old days) can be used for mixing in circuits with a relatively low component count.

Amplitude modulation

Superheterodyne receivers can be used with a variety of modulation schemes, but we will just refer to amplitude modulation (AM) in this article to keep things simple. Before discussing the receiver, it is worth looking at AM signals, so we know what the receiver is dealing with. As the name suggests amplitude modulation involves changing the amplitude of a fixed frequency carrier wave in proportion to the message signal. The carrier signal (S_C) is a high-frequency (RF) sinusoid at frequency f_C and amplitude A_C, which we can write as:

$$S_C = A_C \cos(2\pi f_C t)$$

Note that the 2π factor converts the ordinary frequency of the signal (f_C) in hertz to an angular frequency (ω) in radians. The message signal (S_M) is at a lower frequency (for example, audio) and varies the instantaneous amplitude of the carrier to give the modulated signal (S_{AM}):

$$s_{AM} = A_c(1 + kS_M)$$

In this expression, k is the modulating factor, which is a value greater than zero. The value of k, together with the relative amplitudes of carrier and message determine the modulation depth (m), that is the amplitude of the modulation relative to the carrier. For a sinusoidal message of amplitude A_M the modulation depth is:

$$m = \frac{kA_M}{A_C} \times 100\%$$

The maximum modulation depth without causing distortion is 100%, beyond that we have overmodulation. Real AM voice/music radio systems have modulation depths well below this, maybe 30% to 60% in sinewave terms, but because real signals do not have constant amplitude their modulation depth is expressed in rms (root mean square) terms, where the typical values may be in the range 20% to 40% rms (for example, see the International Telecommunications Union report ITU-R BS.2433-0 (10/2018)).

AM signals

For a sinusoidal message at frequency f_M and amplitude A_M, that is given by:

$$S_M = A_M \cos(2\pi f_M t)$$

The resulting modulated signal, using the equation above, is:

$$s_{AM} = A_c(1 + kA_m \cos(2\pi f_m t)) \cos(2\pi f_c t)$$

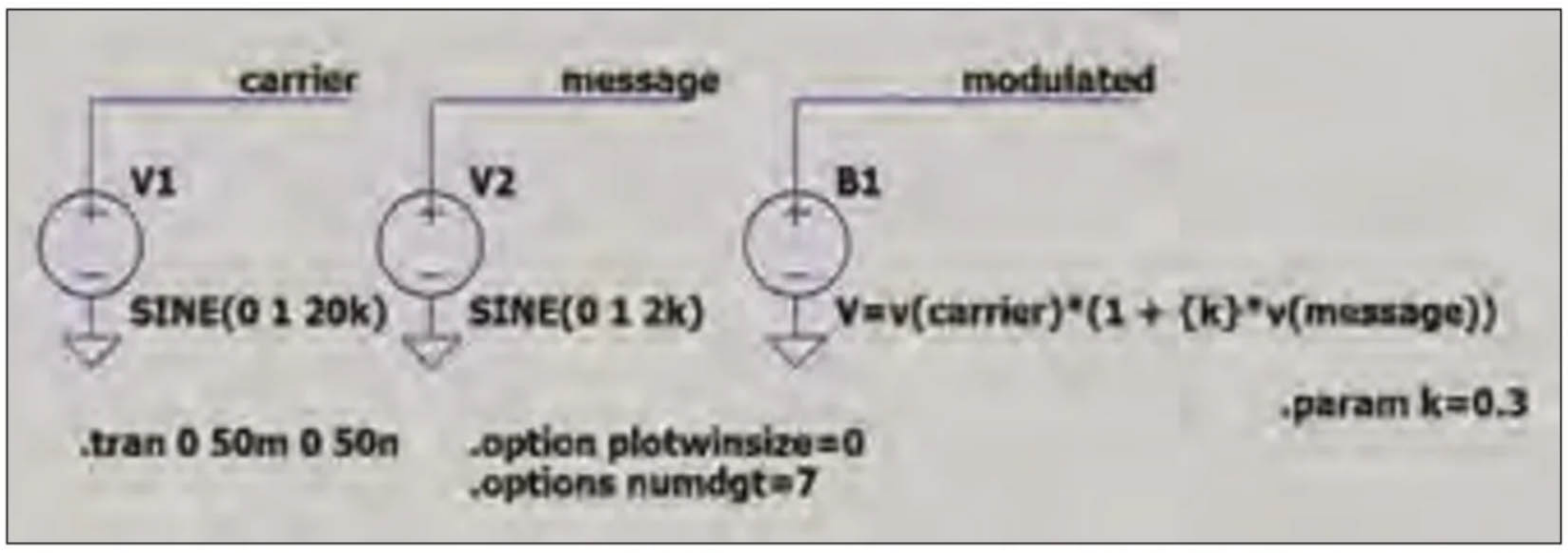
Multiplying out:

$$s_{AM} = A_C \cos(2\pi f_C t) + kA_m \cos(2\pi f_c t) \cos(2\pi f_M t)$$

The signal is equivalent to the carrier plus the carrier multiplied by the message. Based on this and using a similar approach

Introduction to LTspice

Want to learn the basics of LTspice? Ian Bell wrote an excellent series of *Circuit Surgery* articles to get you up and running, see *PE* October 2018 to January 2019, and July/August 2020. All issues are available in print and PDF from the *PE* website: **https://bit.ly/pe-backissues**



```
SINE(0 1 20k)
SINE(0 1 2k)
V=v(carrier)*(1 + {k}*v(message))
.param k=0.3
.tran 0 50m 0 50n
.option plotwinsize=0
.options numdgt=7
```

Fig.1. LTspice schematic for behavioural simulation of amplitude modulation.

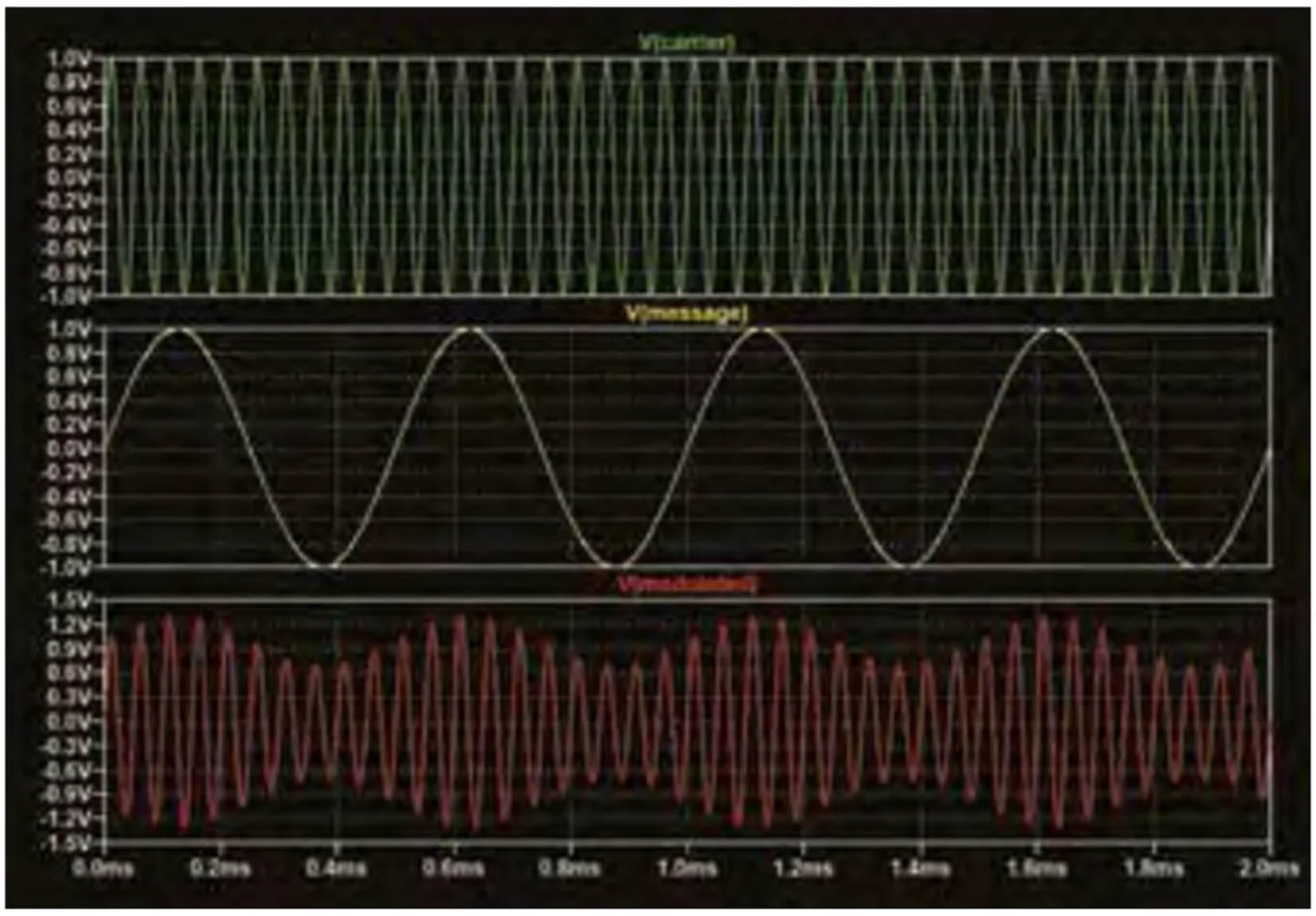
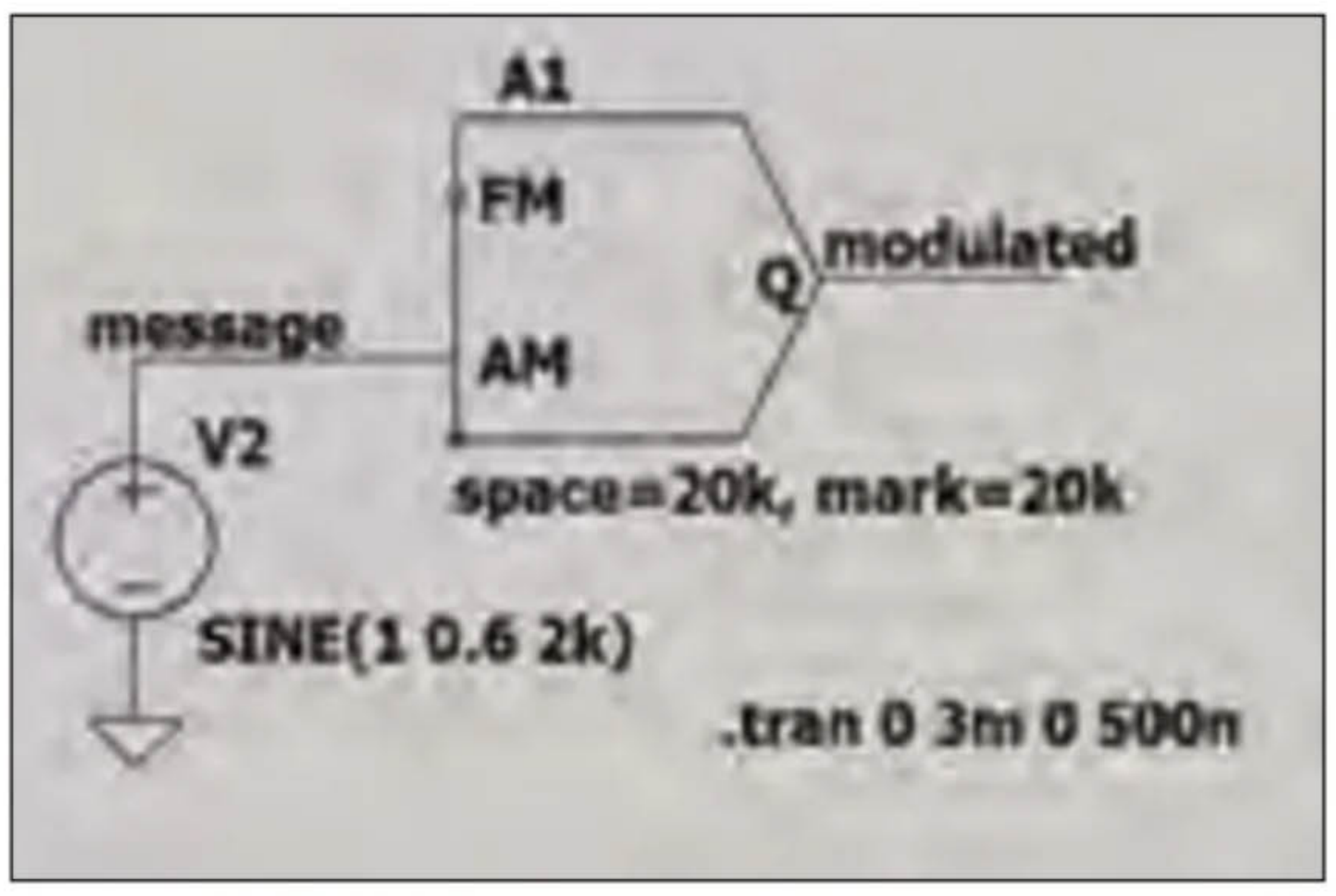


Fig.2. Waveform results from the circuit in Fig.1 with *k* = 0.3 (30%).

to that used for mixers last month, we can create an LTspice behavioural simulation of amplitude modulation (see Fig.1). Like last month, to make it easier to see both the carrier and message waveforms, we are not using typical radio frequencies for the carrier. In the example the value of the modulation factor (*k*) is set up as a parameter.

Fig.2 shows the results from the simulation in Fig.1 for *k* = 0.3 (30%). Fig.3 shows the modulated waveform for *k* = 0.6 (60%). As mentioned last month, when considering the operation of radio systems, we are often more interested in the signal spectra rather than the waveforms in the time domain. Therefore, the simulation is again configured to facilitate viewing of the spectrum with LTspice's FFT function.

In the circuit in Fig.1, we used a behavioural source to implement an AM modulator. An alternative approach is to use the ideal modulator component that is available in LTspice. This can be found in the 'Special Functions' folder of the component selector. It provides both amplitude and frequency modulation (AM and FM) functionality. It has two parameters – mark and space – which set the upper and lower FM frequencies. These should be the set to the same value, equal to the carrier frequency, for AM. An example circuit with the modulator component configured for AM is shown in Fig.4. The example uses a 0.6V-amplitude sinewave message signal on a 1.0V DC offset, with a 20kHz carrier signal. This produces AM with 60% modulation depth, so the output is the same as in Fig.3. If there is no DC offset on the AM input the modulator component (configured for AM) will act as a multiplying mixer.



```
space=20k, mark=20k
SINE(1 0.6 2k)
.tran 0 3m 0 500n
```

Fig.4. LTspice modulator special function component.

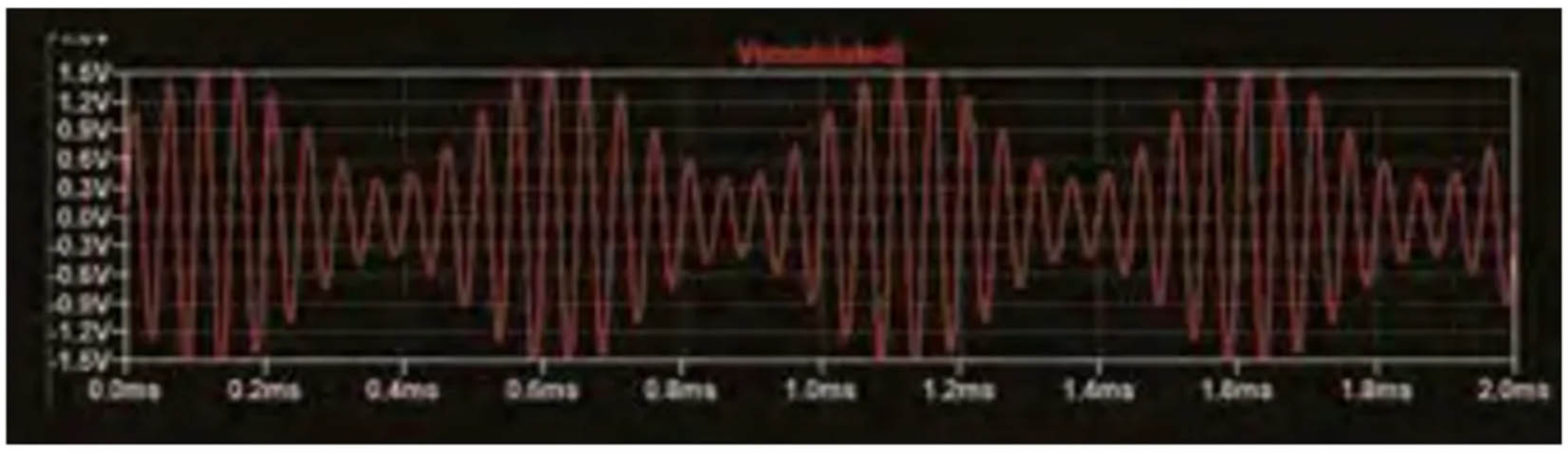


Fig.3. Waveform results from the circuit in Fig.1 with *k* = 0.6 (60%).

Sidebands

From the discussion on mixers last month, we know that the multiply term in the equation for AM with sinusoids given above will produce an output with two signals at the sum and difference frequencies ($f_C - f_M$) and ($f_C + f_M$), the carrier term in the equation means that this frequency (f_C) will also be present in the AM modulator output. This is shown in Fig.5, which is the spectrum (LTspice FFT) for the modulation waveform from the circuit in Fig.1, where the sum (20 + 2 = 22kHz) and difference (20 – 2 = 18kHz) and carrier (20kHz) peaks can be seen.

In the context of modulation, sum and difference frequencies are referred to as the upper and lower sidebands respectively. They are single frequencies in this LTspice example, but in general they comprise the full message bandwidth upshifted to ranges above and below the carrier frequency. This is illustrated in Fig.6. The spectrum on the left of Fig.6 is the baseband and comprises a range of relatively low frequencies (from $f_{m,min}$ to $f_{m,max}$); for example, audio from a few tens of hertz to several kilohertz. Like Fig.4, the frequency axis is linear and includes zero frequency (DC) unlike the logarithmic scales commonly used for plots such as amplifier frequency responses.

The right of Fig.6 shows the spectrum of the AM signal produced by using the baseband signal on the left to modulate a carrier of frequency f_C. The baseband is upshifted to the sum and difference frequencies and so appears both above and below the carrier frequency as the upper and lower sidebands. Note the 'reversal' of the lower sideband – the highest baseband frequency is shifted to the lowest frequency in the lower sideband. The gap between the carrier and sidebands on both sides is equal to the lowest baseband frequency. The plots in Fig.5 are not to scale – the

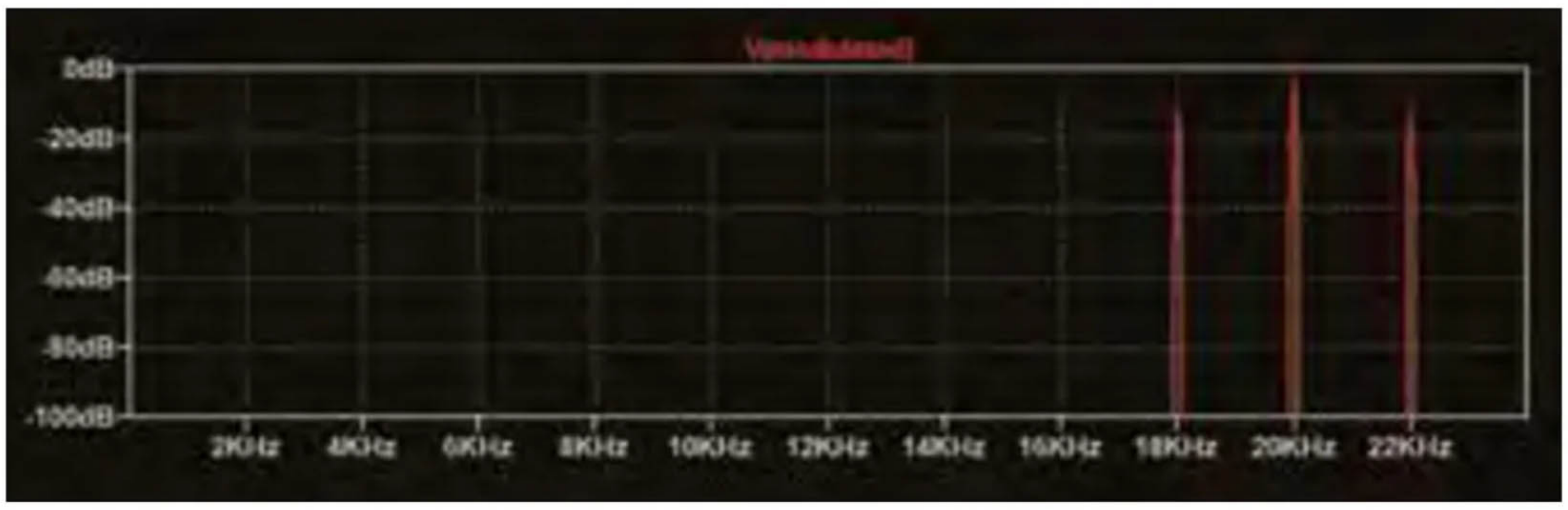


Fig.5. Spectrum of the modulated waveform of the circuit in Fig.1 with $k = 0.6$ (60%).

break in the AM plot axis indicates that a typical carrier frequency is much further along the axis (relative to the size of the sidebands) than where it is located in the drawing.

The full AM signal takes more bandwidth and power to transmit than is strictly necessary. For normal AM the sidebands are symmetric (see Fig.6), so only one needs to be transmitted, halving the bandwidth – this is called Single Sideband (SSB). The carrier contains no message information, so can be reduced in amplitude or removed (referred to as suppressed carrier), which can be applied to both single and double sidebands (SSB-SC and DSB-SC). Not transmitting a sideband and/or the carrier reduces power requirements or increases coverage with the same power. Receiving SSB and suppressed carrier signals is more complex and requires higher receiver performance than full AM, so is generally avoided for commercial AM stations, but is used in other contexts. For simplicity, we will assume full AM signals when discussing receivers here.

Intermediate frequency

As previously explained, a key feature of the superheterodyne receiver is the downshifting of the received signal to a fixed intermediate frequency. The idea of what is required is illustrated in Fig.7. There is a range of possible received signals, that is different carrier signals and their associated sidebands from the various stations or channels that can be received. One of these is selected (by tuning to that station or selecting that channel) and it is downshifted to the fixed IF. The downshifting does not change the shape of the spectrum of the AM signal – it just shifts it to a new centre frequency (f_{IF} instead of f_C). The IF AM signal can then be demodulated to recover the message signal.

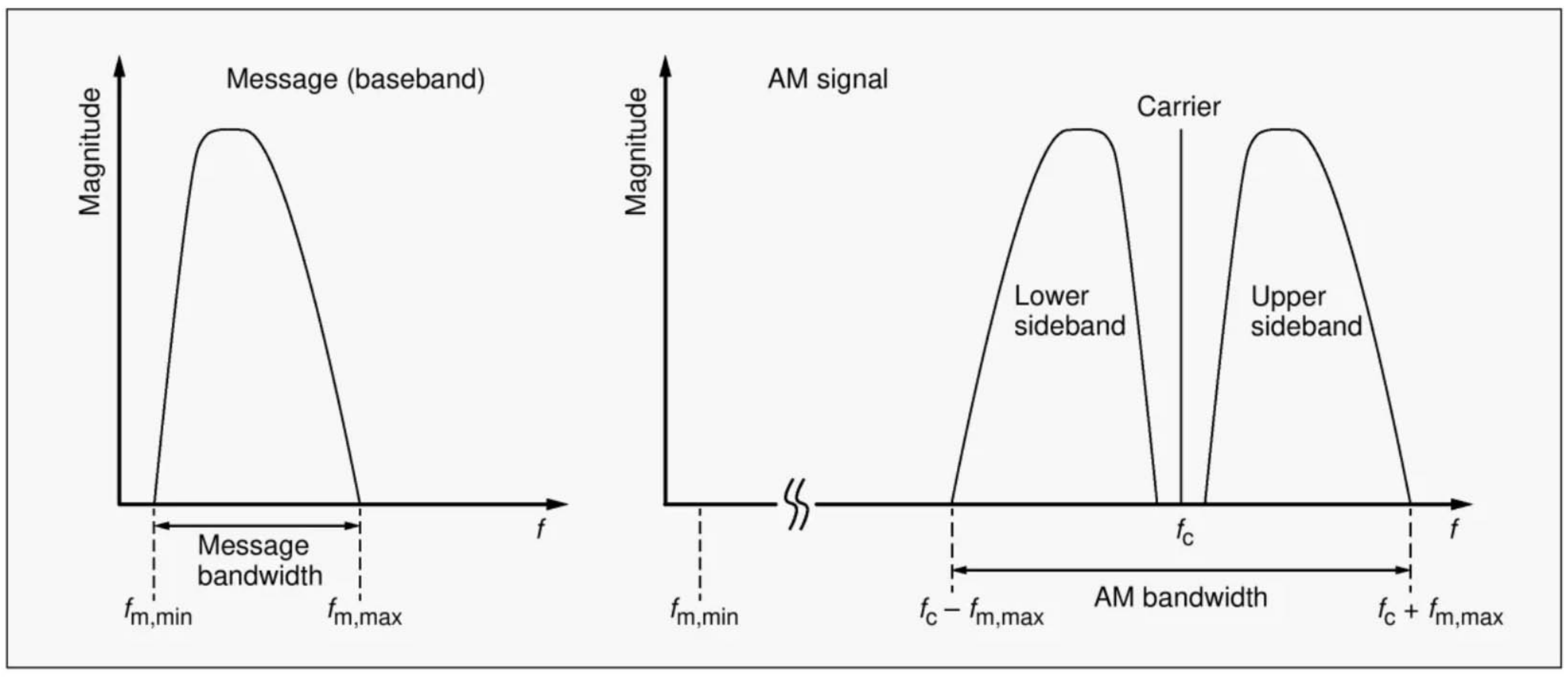


Fig.6. Signal spectra for AM.

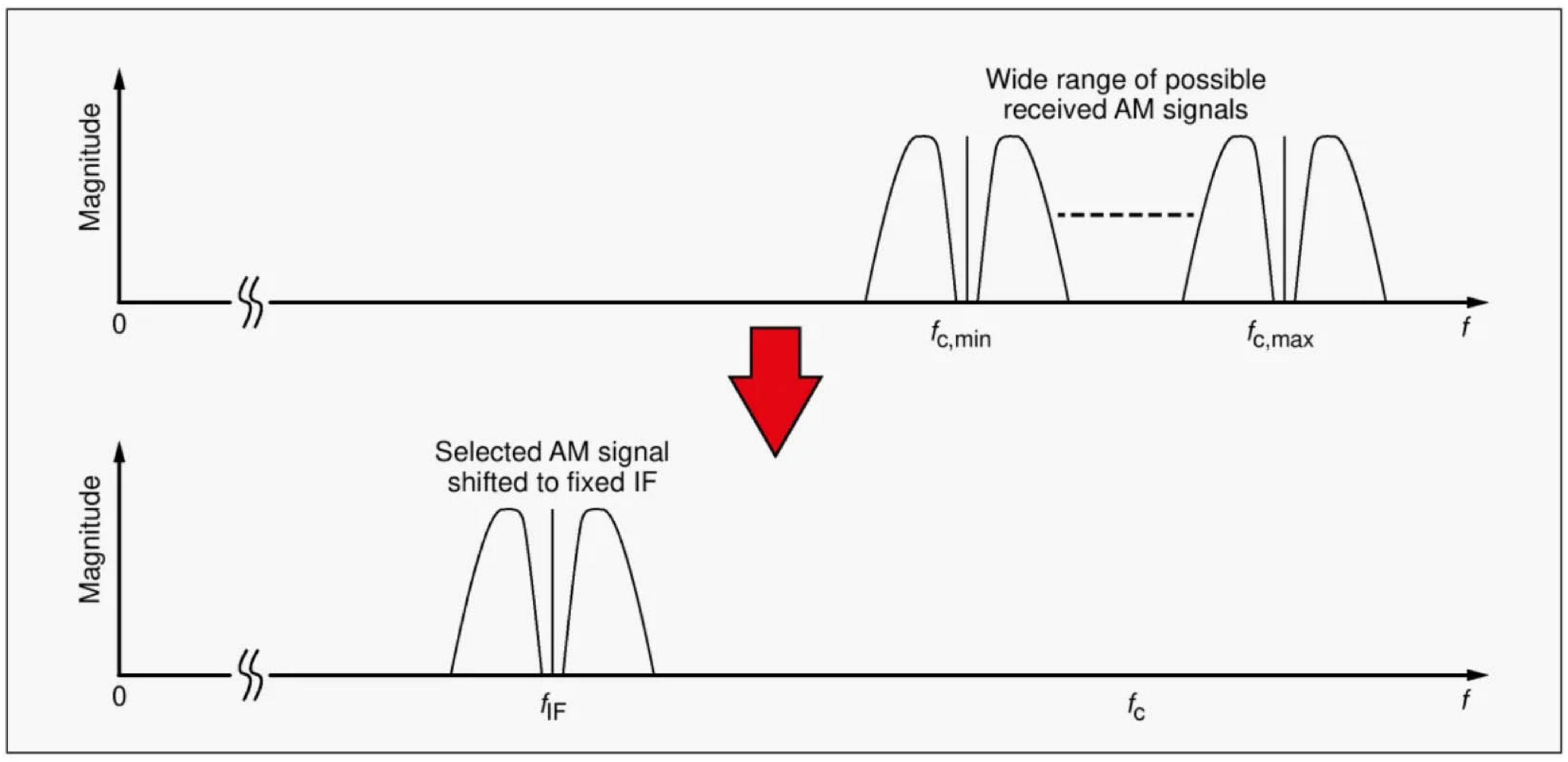

Magnitude
Wide range of possible received AM signals
0
$f_{c,min}$
$f_{c,max}$
f
Magnitude
Selected AM signal shifted to fixed IF
0
f_{IF}
f_c
f

Fig.7. Shifting a received AM signal to IF.

As we know from the detailed discussion of mixing last month, shifting to IF can be achieved by mixing (ideally multiplying) the received signal by a sinusoidal signal at an appropriate frequency. In a receiver, this signal is generated by a local oscillator (LO). The mixer produces sum and difference frequencies, which means that either the sum or difference frequency of the received carrier with respect to the LO frequency must match the required intermediate frequency. Using a local oscillator frequency below the carrier frequency is called 'low-side injection'; if the local oscillator frequency is above the carrier frequency it is 'high-side injection'. Both can be used, but for basic AM high-side injection is more common. The multiple frequencies produced by nonlinear mixers are more likely to produce disruptive signals in the received signal range if low-side injection is used.

Mixing the received carrier at f_C with a high-side local oscillator at f_{LO} produces signals at ($f_{LO} - f_C$) and ($f_{LO} + f_C$), with their sidebands. Assuming we want an IF which is lower than the carrier frequency (it does not have to be) we need $f_{IF} = f_{LO} - f_C$. This means we need to tune the local oscillator to $f_{LO} = f_C + f_{IF}$. We need the local oscillator to be able to tune to $f_C + f_{IF}$ throughout the range of frequencies we want to receive. In addition to the required IF signal at $f_{LO} - f_C$ the mixer will also produces a higher frequency signal at $f_{LO} + f_C$. This needs to be removed by filtering.

As a round-number example, for a carrier range of 1.0MHz to 1.5MHz and an IF of 400kHz (0.4MHz) the local oscillator needs to tune from 1.4MHz (1.0 + 0.4 = 1.4) to 1.9MHz (1.5 + 0.4 = 1.9). The mixer will also produce signals in the range 2.4MHz (1.0 + 1.4 = 2.4) to 3.4MHz (1.5 + 1.9 = 3.4), which need to be filtered out. This example is similar to traditional broadcast AM receivers where an IF of 455kHz was commonly used (from the early days of widespread superhet use). An advantage of high-side injection is that a smaller LO tuning range (ratio of highest to lowest LO frequency) is required than for low-side injection, which makes things easier if the tuning is implemented with a variable capacitor.

IF mixer simulation

We can simulate the IF mixing in LTspice by adding a LO signal and behavioural multiplying mixer to the circuit in Fig.1. This is shown in Fig.8 – the carrier (from source `V1`) is at a higher frequency (80kHz) than in the circuit

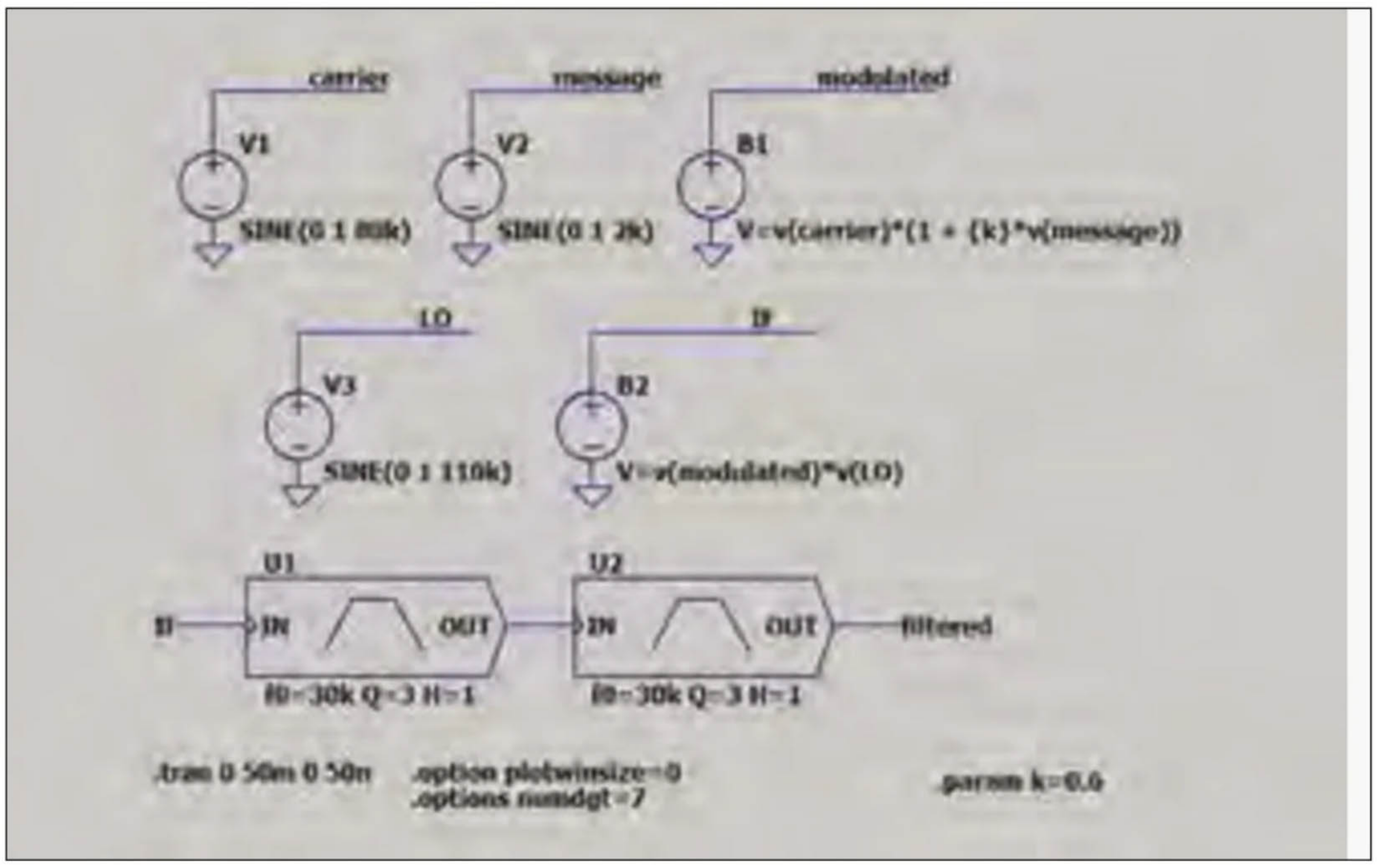


Fig.8. LTspice schematic for behavioural simulation of shifting an AM signal to an intermediate frequency (IF).

in Fig.1, but the modulated signal generation is essentially the same. The modulated signal (signal `modulated` from source `B1`) is multiplied by a 110kHz sinewave from the local oscillator (`LO` signal from source `V3`) using behavioural source `B2`. This produces the intermediate frequency output (signal `IF`) at 30kHz ($f_{IF} = f_{LO} - f_C$ = 110kHz – 80kHz = 30kHz). The schematic includes a filter which we will discuss later.

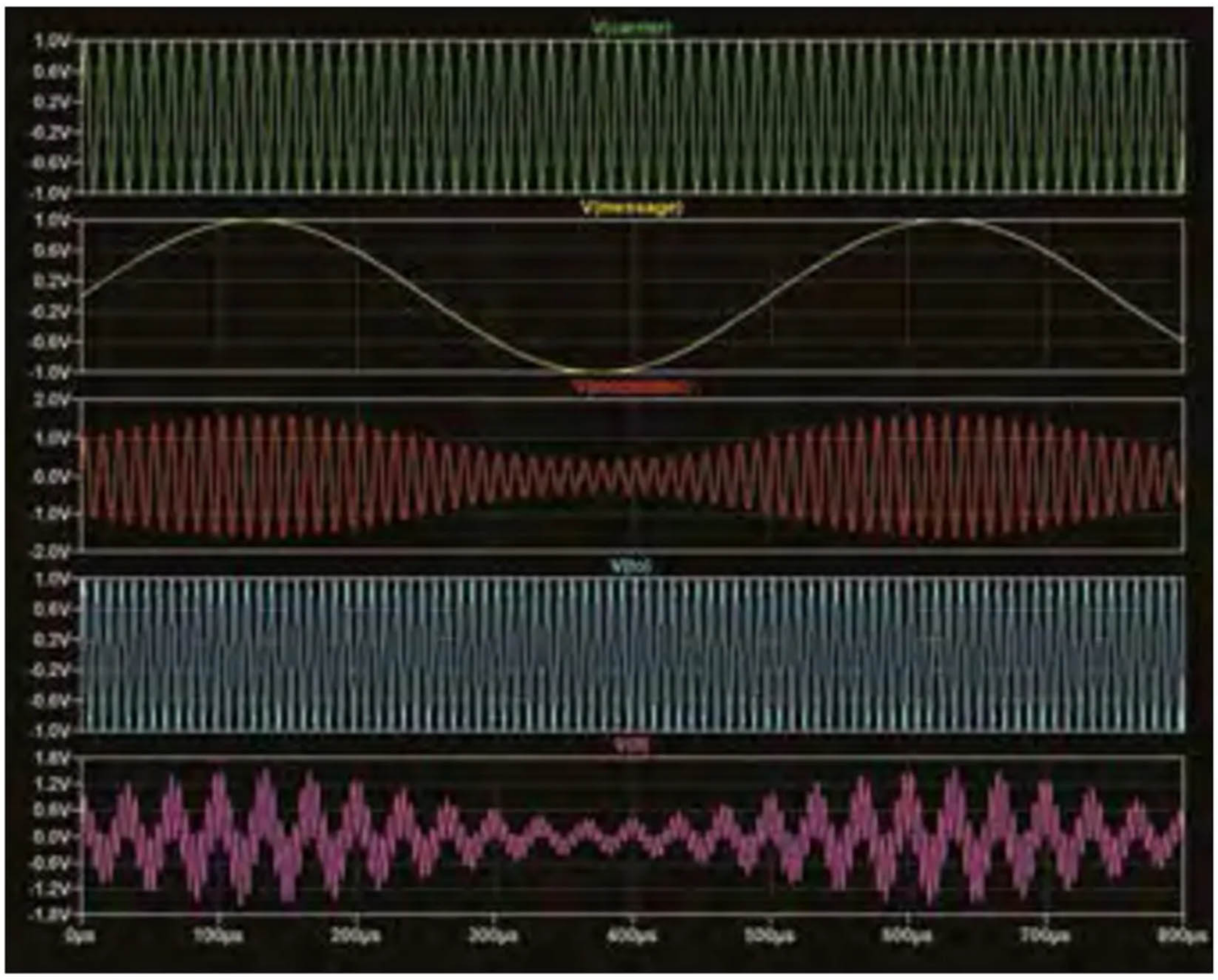


Fig.9. Waveform results from the circuit in Fig.8.

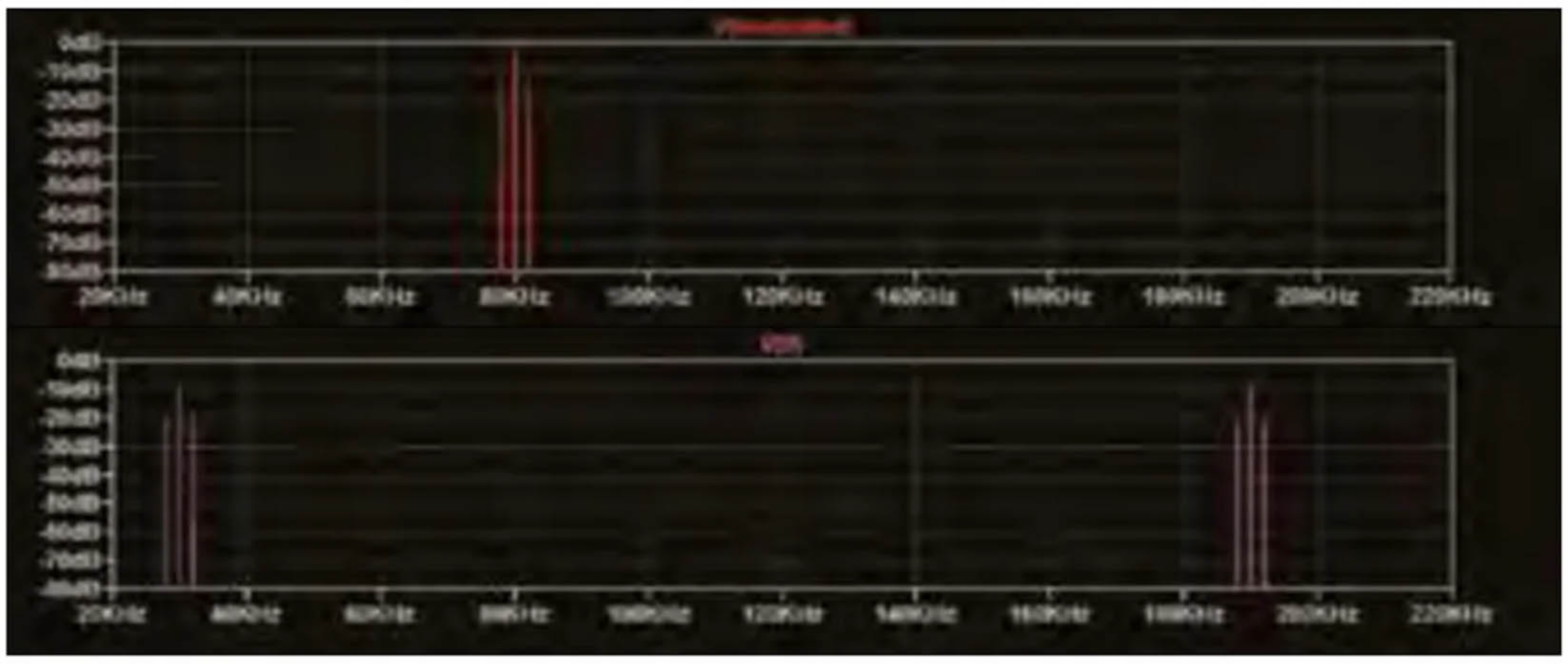


Fig.10. Spectra of 'received' AM and IF waveforms from Fig.9.

The results of simulating the circuit in Fig.8 up to the IF mixer output are shown in Fig.9. The top three traces (carrier (80kHz), message (2kHz) and AM modulated signal) are similar to Fig.2, but the carrier frequency is higher, and the waveforms are zoomed in more. The fourth trace is the local oscillator (LO) at 110kHz. The bottom trace is the IF signal from the mixer. This has a complex-looking waveform, which is difficult to interpret from its shape. It is more useful to look at the spectra.

Fig.10 shows the spectra of the modulated and IF waveforms from Fig.8. It can be seen that the AM waveform comprises the carrier (80kHz) and the two sidebands (at 78kHz and 82kHz), corresponding with Fig.5 and Fig.6, as discussed earlier. The IF spectrum shows the presence of two 'AM' signals of equal amplitudes, one centred on 30kHz and the other on 190kHz. This is the required IF signal centred on 30kHz and the additional signal from the mixer centred on $f_{LO} + f_C$ = 110kHz + 80kHz = 190kHz. Unlike the waveform, the spectrum clearly shows that the IF signal is behaving as expected from mixing (ideal multiplying) the local oscillator and AM signal.

Looking at the lower trace in Fig.10 we see that to obtain the desired signal, that is the AM signal centred at the IF frequency of 30kHz on its own, we need to filter the IF mixer output to remove the component of the waveform centred at 190kHz. In this simplified example there are no other signals present in the spectrum, but in general the IF mixer output spectrum will contain many other significant peaks. These will include the result of mixing signals from adjacent radio stations/channels with the local oscillator, and additional spectral components resulting from non-ideal mixer behaviour (see last month's discussion). Thus, a bandpass filter is required to remove all the unwanted parts of the IF spectrum before the IF signal can be demodulated to recover the message.

Tuning

It is not the whole story, as we will see shortly, but the tuning of a superheterodyne receiver to the desired station/channel is fundamentally achieved by a combination of the local oscillator frequency, which selects which received frequency is shifted to the IF, and the bandpass filter after the IF mixer which removes everything apart from the wanted signal. This

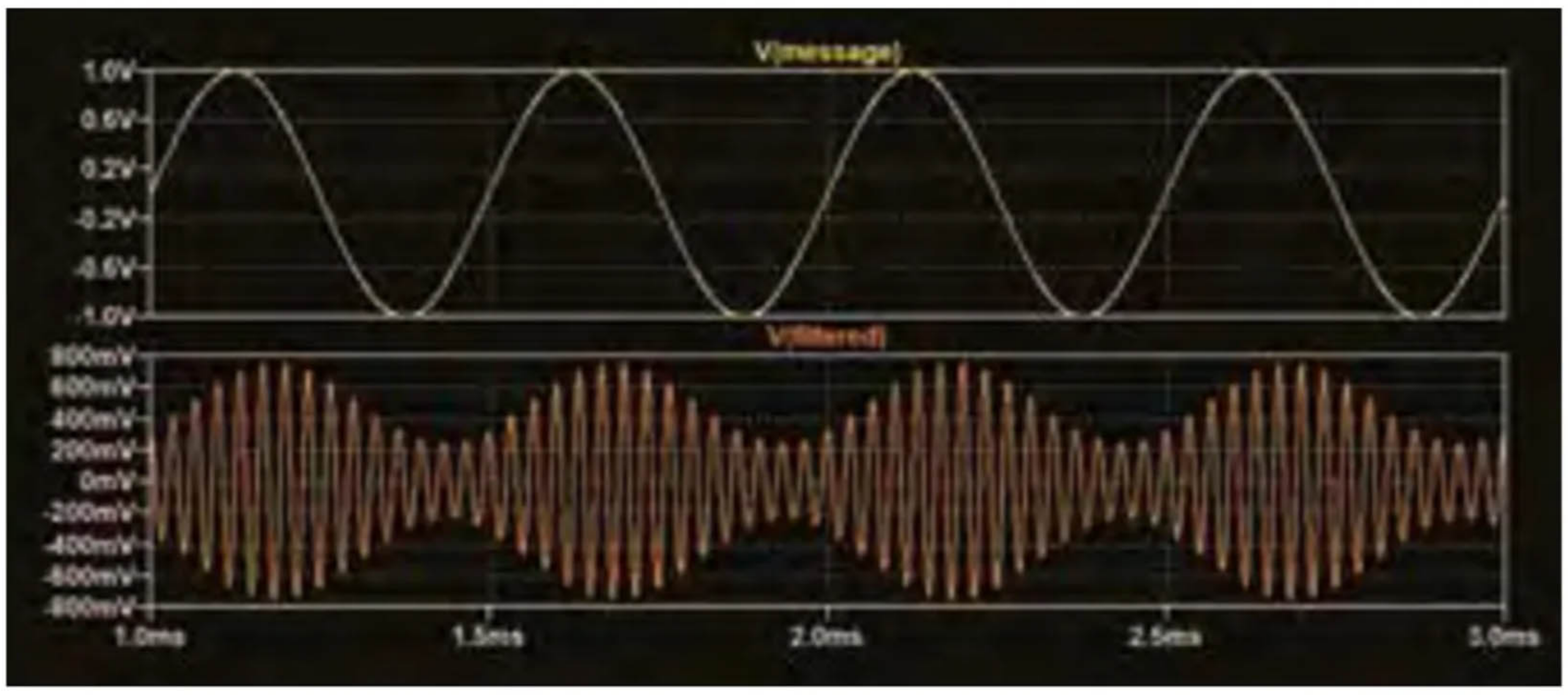


Fig.11. Waveform of filtered IF mixer output from the circuit in Fig.9.

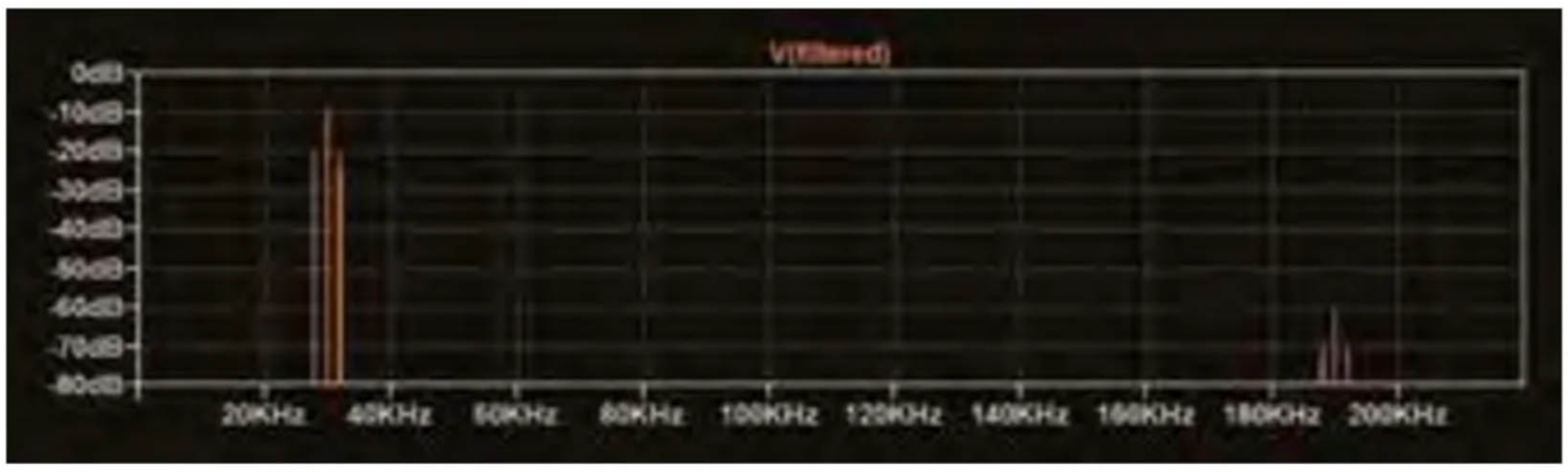


Fig.12. Spectra of filtered IF waveform from the circuit in Fig.9.

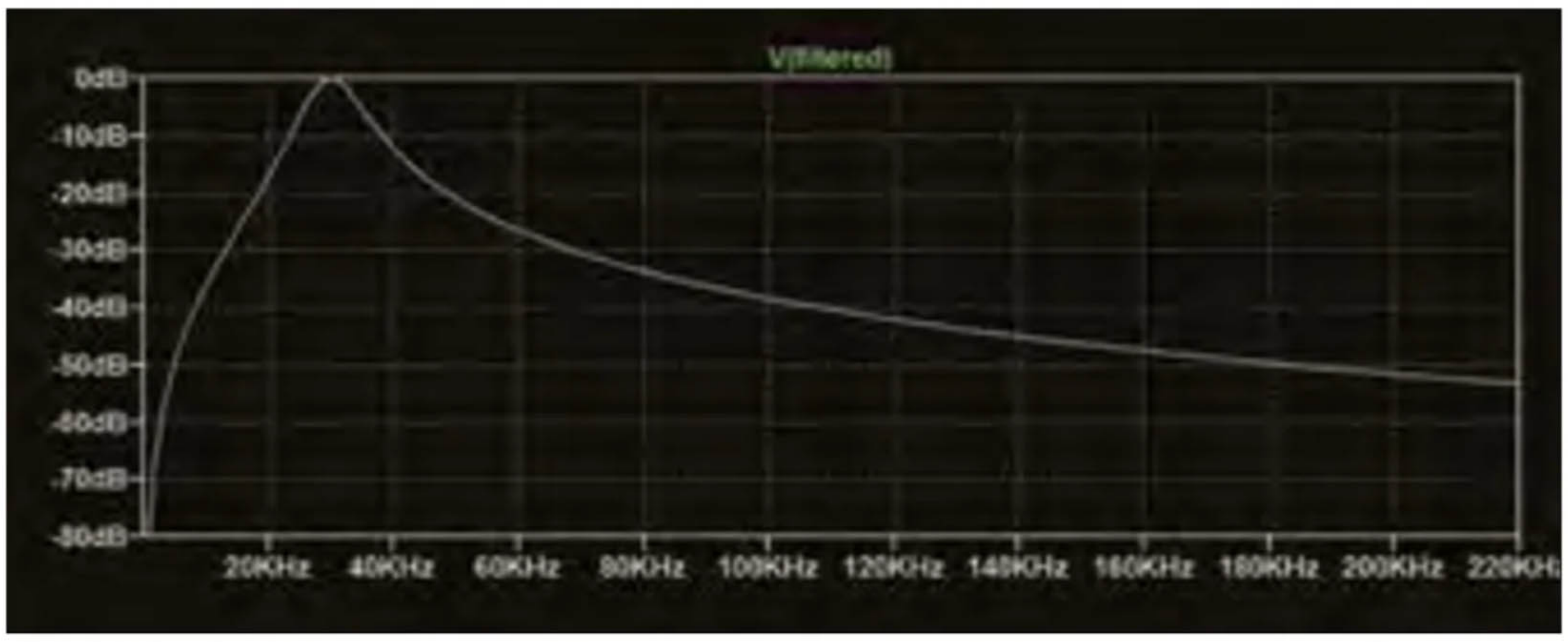


Fig.13. Frequency response of the filter (`U1` and `U2`) in Fig.9.

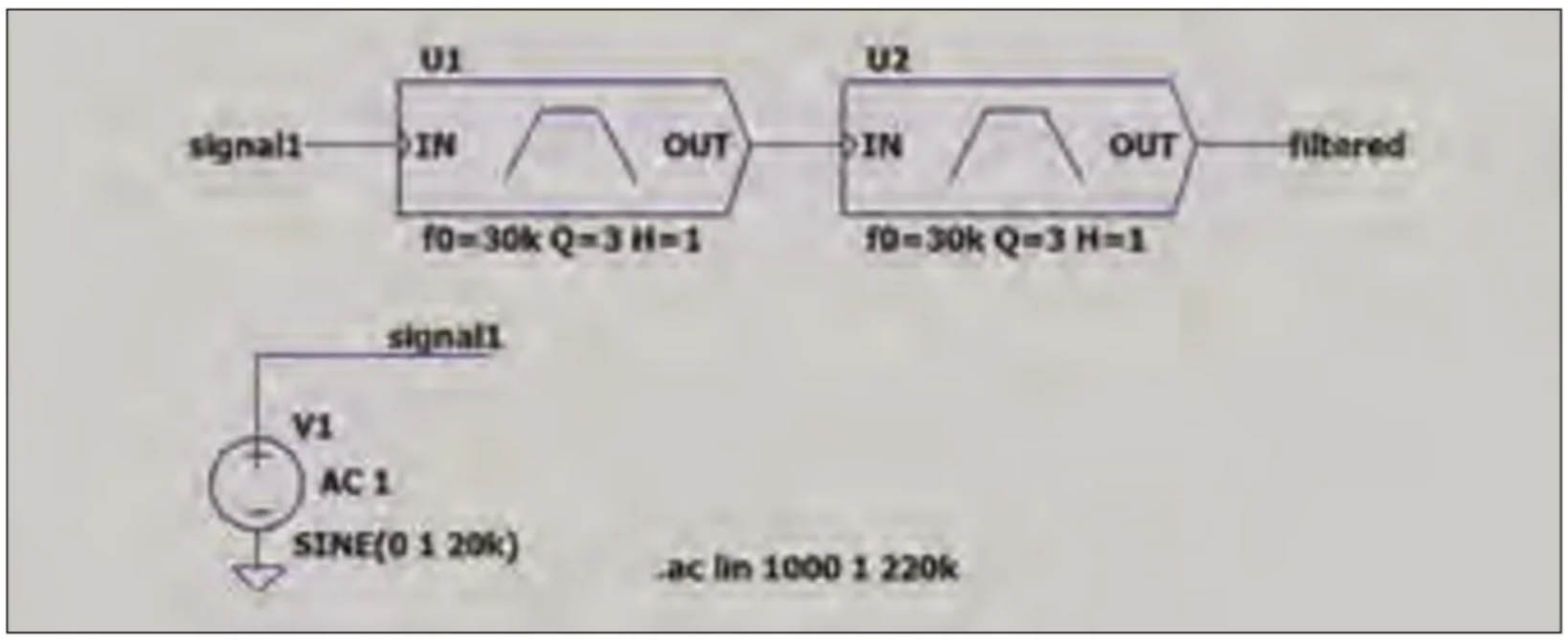


Fig.14. LTspice circuit to obtain the frequency response in Fig.13.

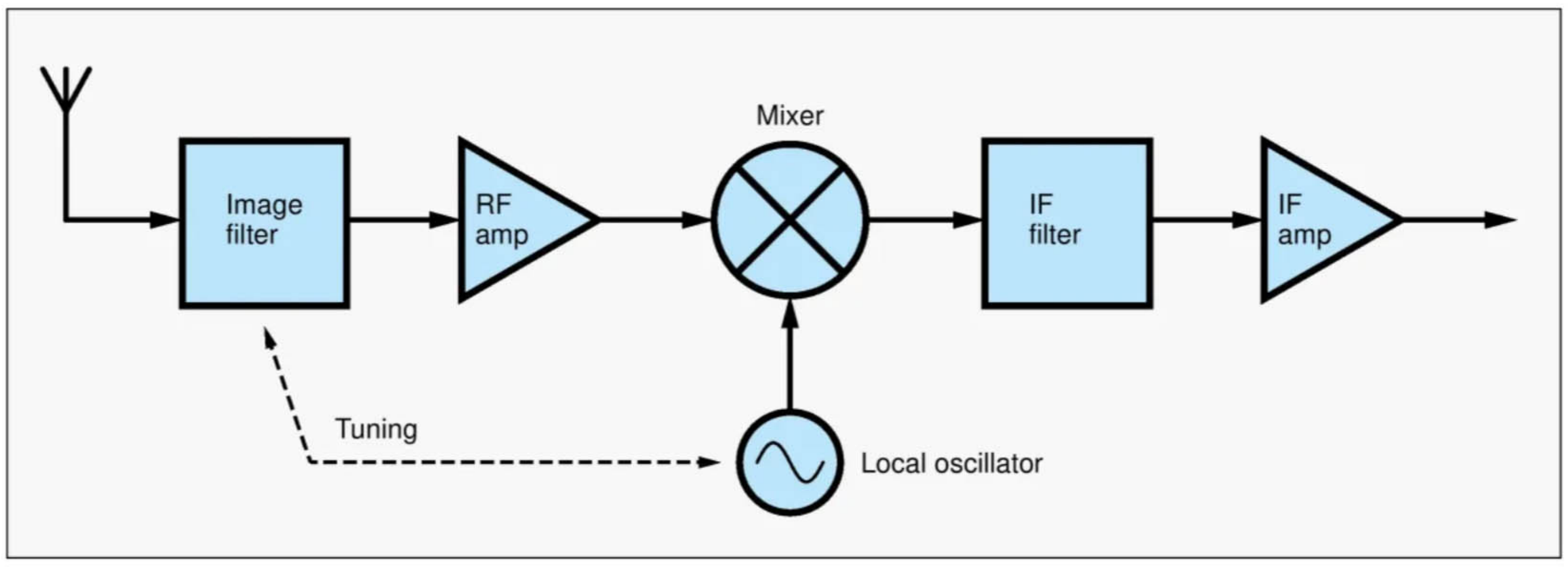


Fig.15. Superheterodyne receiver structure.

requires a filter with a sharp cutoff outside the bandwidth of the received signal; however, because the IF is at *fixed* frequency a *fixed* filter can be used, which is relatively easy to achieve.

The IF filter was implemented using LC circuits in the earliest superheterodyne radios, but later replaced by ceramic filter components which provide better accuracy at low cost. As mentioned above, 455kHz is the traditional IF frequency for broadcast AM receivers and many ceramic filters for this (and other related) IF frequencies were manufactured. However, some of these specific components may be harder to source now as technology has moved on. (eBay may be your best bet, as is scavenging old radio equipment.) These days, filtering (and other processing) of IF signals can often be achieved using DSP (digital signal processing).

A bandpass filter is implemented in the circuit in Fig.8 using two LTspice second-order behavioural bandpass filters (`U1` and `U2`). These are configured as a fourth-order bandpass filter, centred on the IF frequency of 30kHz, with a bandwidth which means that message signal (sidebands) will not be significantly attenuated. This filter is for illustration using these example waveforms and chosen for convenience of quick set-up in LTspice. It is not necessarily similar to the requirements for real radio signals because the IF, LO and carrier frequencies in the example are very low for purposes of displaying the waveforms, and there are no unwanted signals very close to the IF frequency in the example.

The waveform of the filtered IF mixer output (signal `filtered`) for the circuit in Fig.8 is shown in Fig.11 with the original message signal for comparison. We can see that it looks like an AM signal modulated with the 2kHz sinewave message. The spectrum of the filtered IF mixer output is shown in Fig.12 and the frequency response of the filter is shown in Fig.13 over the same range as the spectrum. The frequency response was obtained using the circuit in Fig.14. Comparison of the filtered mixer output spectrum with the unfiltered spectrum in Fig.10 shows that the signal centred at 190kHz has been significantly attenuated.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website:
https://bit.ly/pe-downloads

Image frequency

Previously, we discussed using a local oscillator at frequency $f_{LO} = f_C + f_{IF}$ to tune to our required carrier frequency (f_C) and shift the signal to the IF ($f_{IF} = f_{LO} - f_C$). However, the mixer, with the local oscillator at f_{LO} as one of its inputs, will also shift a different frequency to f_{IF}, specifically $f_{IF} = f_{Im} - f_{LO}$, where f_{Im} is known as the image frequency. We have $f_{Im} = f_C + f_{LO}$. For example, using the same round numbers as above, for f_C = 1.0MHz and an IF of 400kHz (0.4MHz) the local oscillator needs to be at 1.4MHz and therefore the image frequency is at 1.8MHz (1.4 + 0.4 = 1.8MHz). In this example, if the receiver picks up a signal at 1.8MHz it will be shifted to the IF along with the wanted signal. Because it is then at the same frequency, the image cannot be separated from the wanted signal by filtering after the mixer.

In general, we have to assume that received signals will be present at the image frequency, so they must be removed before the mixer. This requires a filter before the mixer, called the image filter or preselection filter, which may be tuneable to track with the local oscillator. However, the requirements for this filter are a lot less severe than if we tried to filter the required station/channel directly from the RF signal received from the antenna. In a superhet the more demanding filtering is done by the fixed frequency IF filter, as described earlier. The preceding discussion leads to the structure of a superheterodyne receiver as shown in Fig.15. There are of course variations on this theme – for example, there may be another filter before the image filter to remove all signals outside the band the receiver is designed to work with. The next stage after the IF amplifier is detection or demodulation of the IF signal, which we will look at next month.

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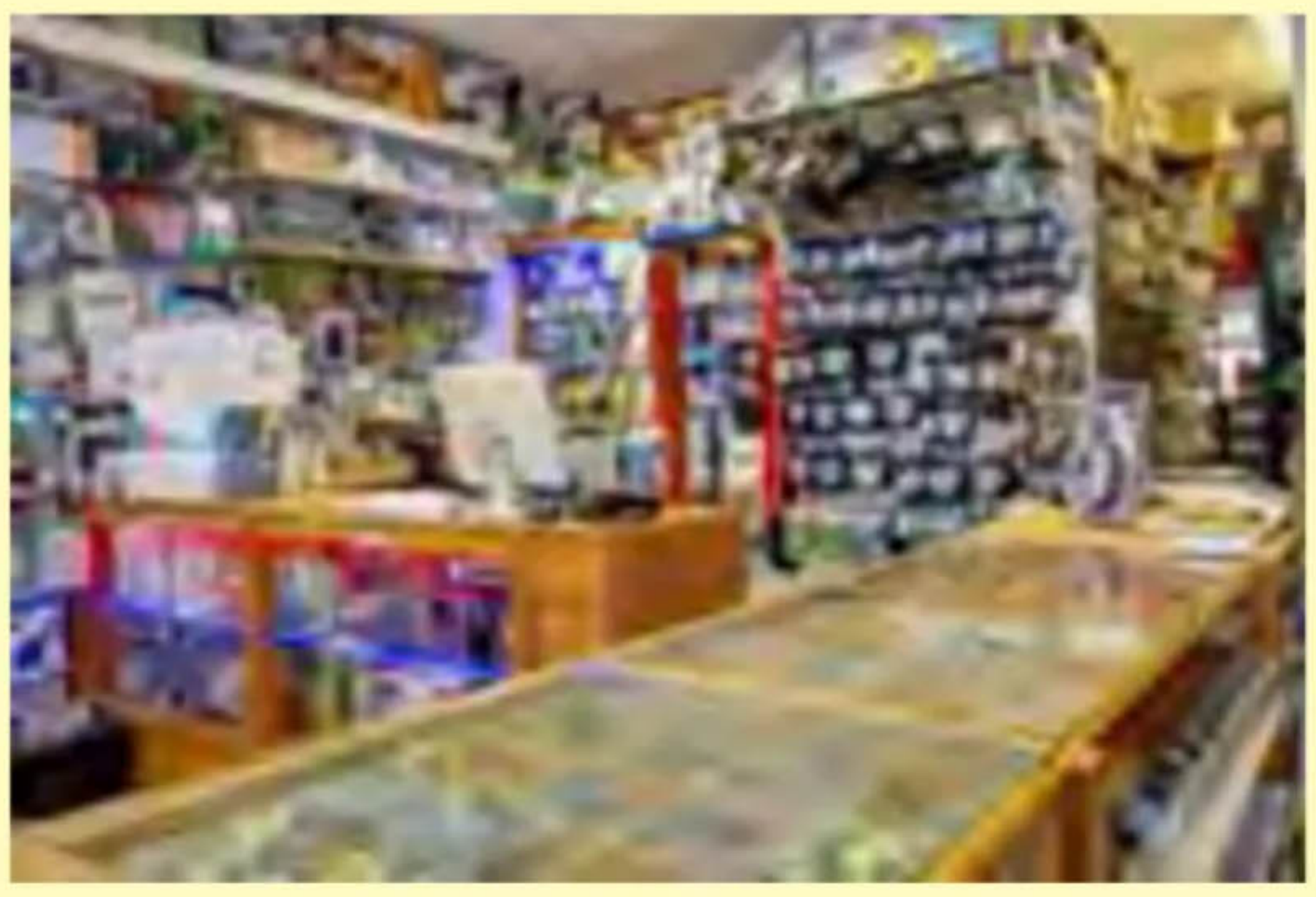

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Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio Communications Test Set – £800

MITCHELECTRONICS

Learn the basics of electronics with Robin Mitchell

The 555 Timer IC – Part 2: Enter Logic

MitchElectronics is a series of projects by Robin Mitchell that introduces beginners to useful, simple, easy-to-understand circuit designs. Each month, he will introduce fundamental components, theory and ideas used in electronics. The series will cover both analogue and digital electronics.

In last month's article – The 555 *Timer IC Part 1* – we looked at how the iconic 555 timer IC can be used as an astable and monostable, as well as learning about a number of fundamental circuit components, including resistors, capacitors and LEDs. This month, we will learn how to use the astable and monostable circuits in practical applications, including the MitchElectronics *4017 Light Chaser*, *Traffic Light* and *Electronic Dice* kits. Plus we will introduce a number of new circuit concepts, including a start on how logic chips work.

Fundamentals

Before we can jump into the practical applications of the 555 astable and monostable circuits, we first need to discuss several new fundamental components and circuit ideas: diodes, potential dividers, a deeper dive into the 555 IC, logic, and an introduction to the cheap and easy-to-use CMOS 4000 series of logic ICs.

What are diodes?

Diodes are one of the most fundamental and important components (next to resistors and capacitors) and are used to control the flow of current. Like capacitors and resistors, diodes are passive components meaning that they are unable to control a current flow (whereas devices like transistors, op amps and logic chips are active components). Diodes are made of two layers of subtly different kinds of semiconductors, and just like the LEDs (light-emitting diodes) we met last month, diodes only conduct current in one direction. You can think of them as the electronic equivalent of a one-way valve in plumbing.

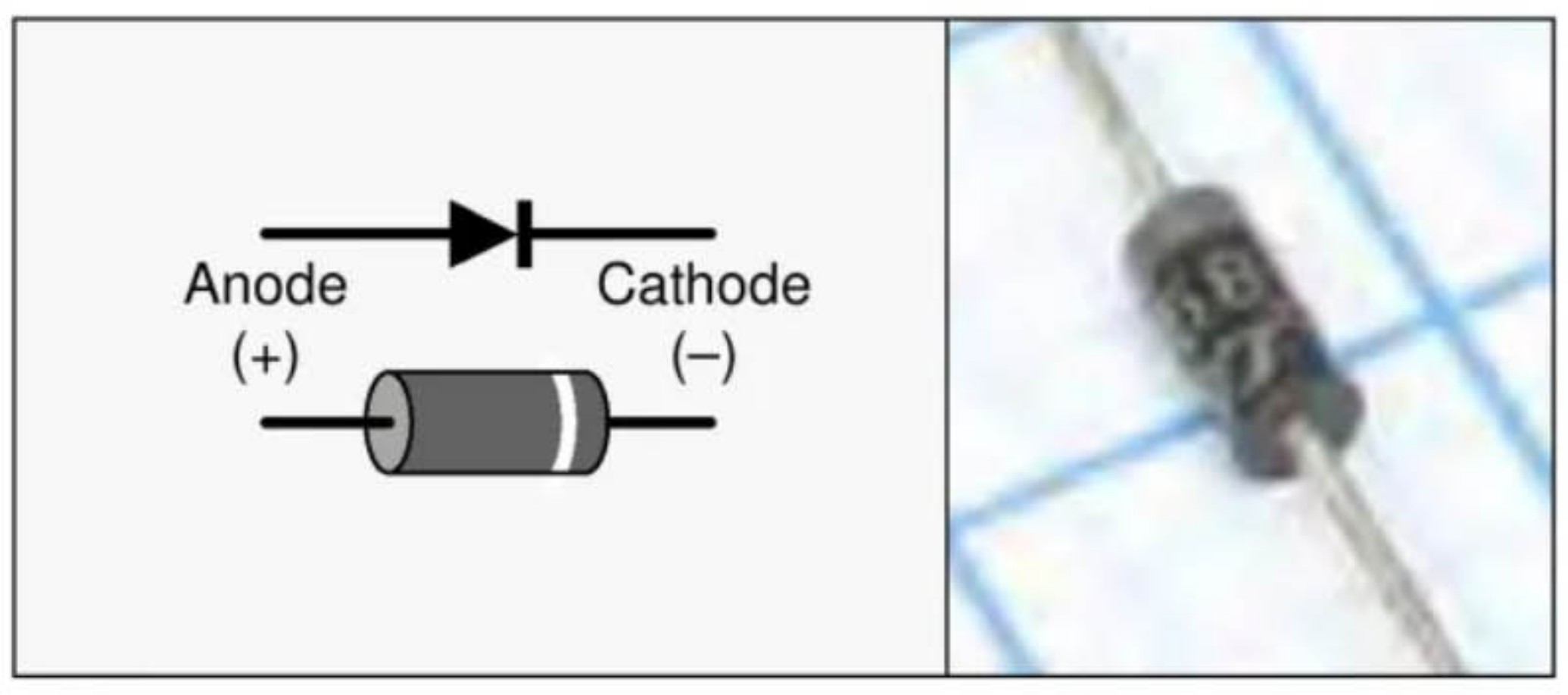


Fig. 1. Diode schematic symbol and 1N5817 diode.

Diodes have two pins: the 'anode' which must be positive compared to the other, called the 'cathode' if current is to flow – see Fig.1. This is a vital point for diodes, current can only flow through a diode from the anode to the cathode. This makes diodes extremely useful for 'rectification', where alternating current (AC) is converted into a direct current (DC), as well as for circuit protection and preventing reversed power supplies from damaging circuits (such as inserting batteries in the wrong direction). Diodes are cheap, widely used and have many uses. You will encounter them in all shapes and sizes as you build and study electronic circuits.

Diodes can be made from various semiconductors, but the most common material for diodes is silicon. (Older devices were often germanium.) To make a diode, two differently doped pieces of semiconductor, called 'n-type', and 'p-type' are fused together – see Fig.2. n-type semiconductors are doped with materials such as phosphorus, arsenic or antimony, which give a semiconductor material an excess number of electrons (hence, N-type for *n*egatively doped). p-type semiconductors are doped with materials such as boron or gallium, which give a semiconductor material a deficit of electrons resulting in net *p*ositive doping (hence, p-type).

Let's look at the electrical characteristics of diodes – how its current flow for a given applied voltage varies.

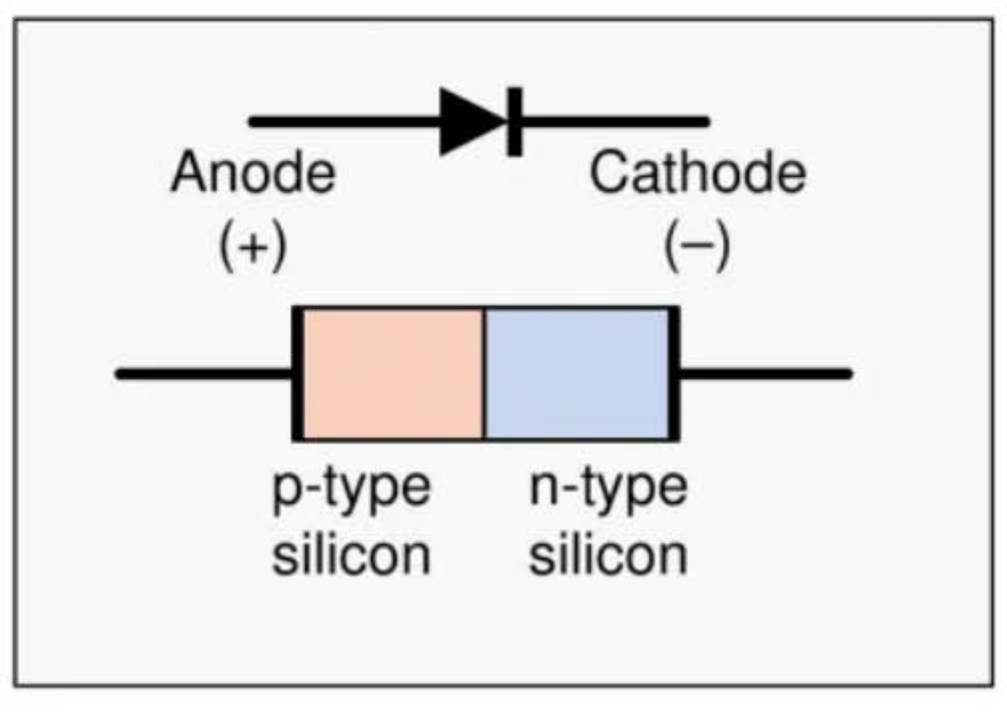


Fig. 2. Diode semiconductor structure.

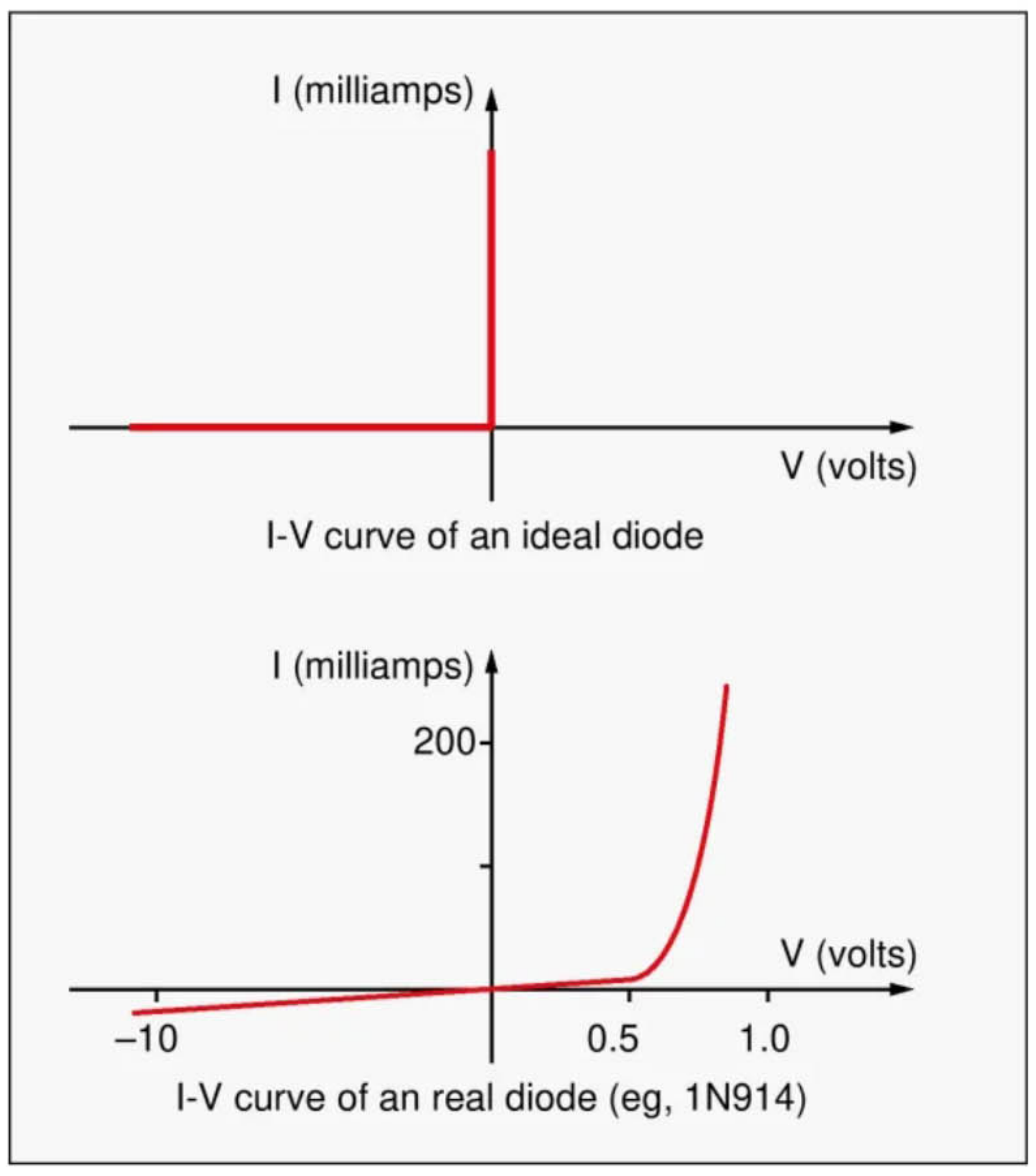


Fig. 3. Voltage -current characteristics of an ideal diode vs real diode.

An ideal or 'perfect' diode conducts current in one direction only, with no voltage drop across it; zero resistance when conducting, and infinite resistance when not conducting. In reality, diodes are far from perfect, and have a few important characteristics, including a forward voltage drop, and a non-linear current behavior.

Looking at the graph shown in Fig.3, barely any current flows through a diode until the voltage across the diode goes beyond its 'forward voltage', often abbreviated to V_f. This can be thought of as the voltage needed to turn on the diode and make it function. When a diode has sufficient voltage across it to make it conduct, it is said to be forward biased. For silicon diodes, this forward voltage is typically around 0.7V, but it can be as low as 0.5V and as high as 1V (and remember it is typically 1-2V for LEDs).

One neat feature of the forward voltages is that because the voltage across a diode cannot exceed the forward voltage of the diode (when used within the diode's safe operating parameters), diodes can be used to clamp voltages. If the input voltage shown in Fig.4 exceeds the forward

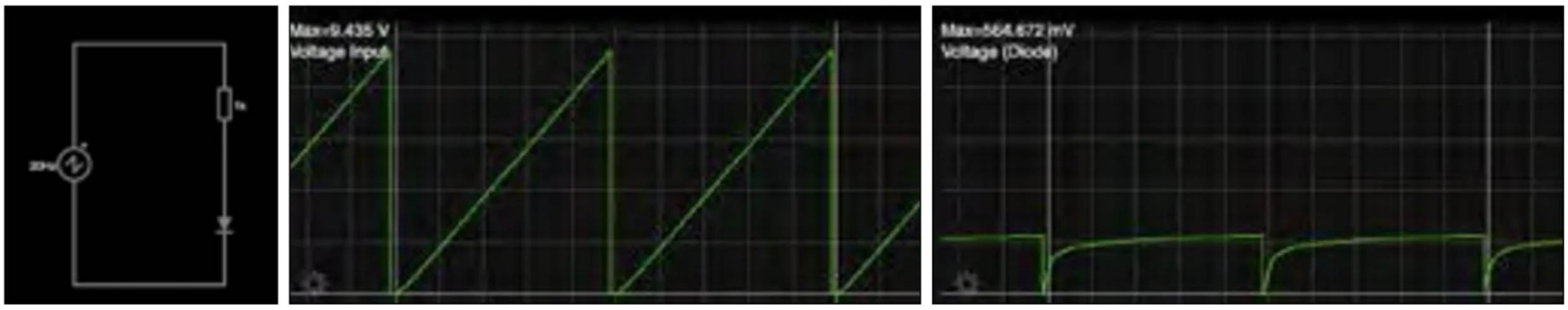


Fig. 4. Diode-resistor circuit comparing the voltage across the diode and resistor in series.

voltage, then the remaining voltage is 'dumped' across the series resistor. This can be handy for protecting circuits and devices that may be damaged by excessively large input voltages, such as most integrated circuits.

The two diodes that MitchElectronics kits use are the 1N4148 signal diode and the 1N5817 Schottky diode. These are very common in electronic circuits, with the 1N4148 being great for low-voltage, low-current signals, while the 1N5817 is great for rectifying power, thanks to its maximum forward current of 1A.

What are potential dividers?

A potential divider is a special resistor combination that, as the name suggests, can be used to divide a potential, ie, a voltage. (Remember, 'potential' is just a slightly archaic term for 'voltage'.) Whenever you hear the term 'potential divider' it simply means to divide/reduce a voltage by a controlled amount.

So how does it work? When two (or more) resistors are placed in series (in line, as opposed to in parallel), the voltage across each resistor will be proportional to its resistance, such that the larger a resistor is, the larger the proportion of the input voltage across it.

The most basic and most common potential divider consists of just two resistors, as shown in Fig.5: R_1, R_2, an input voltage and an output voltage. The voltage across R_1 *and* R_2 is the input voltage, referred to as V_{in}, and the voltage across R_2 is the output voltage, V_{out}.

So how do we calculate V_{out}? First let's calculate the current running through both resistors using Ohm's law:

$$V = IR$$

Or dividing both sides by R we get:

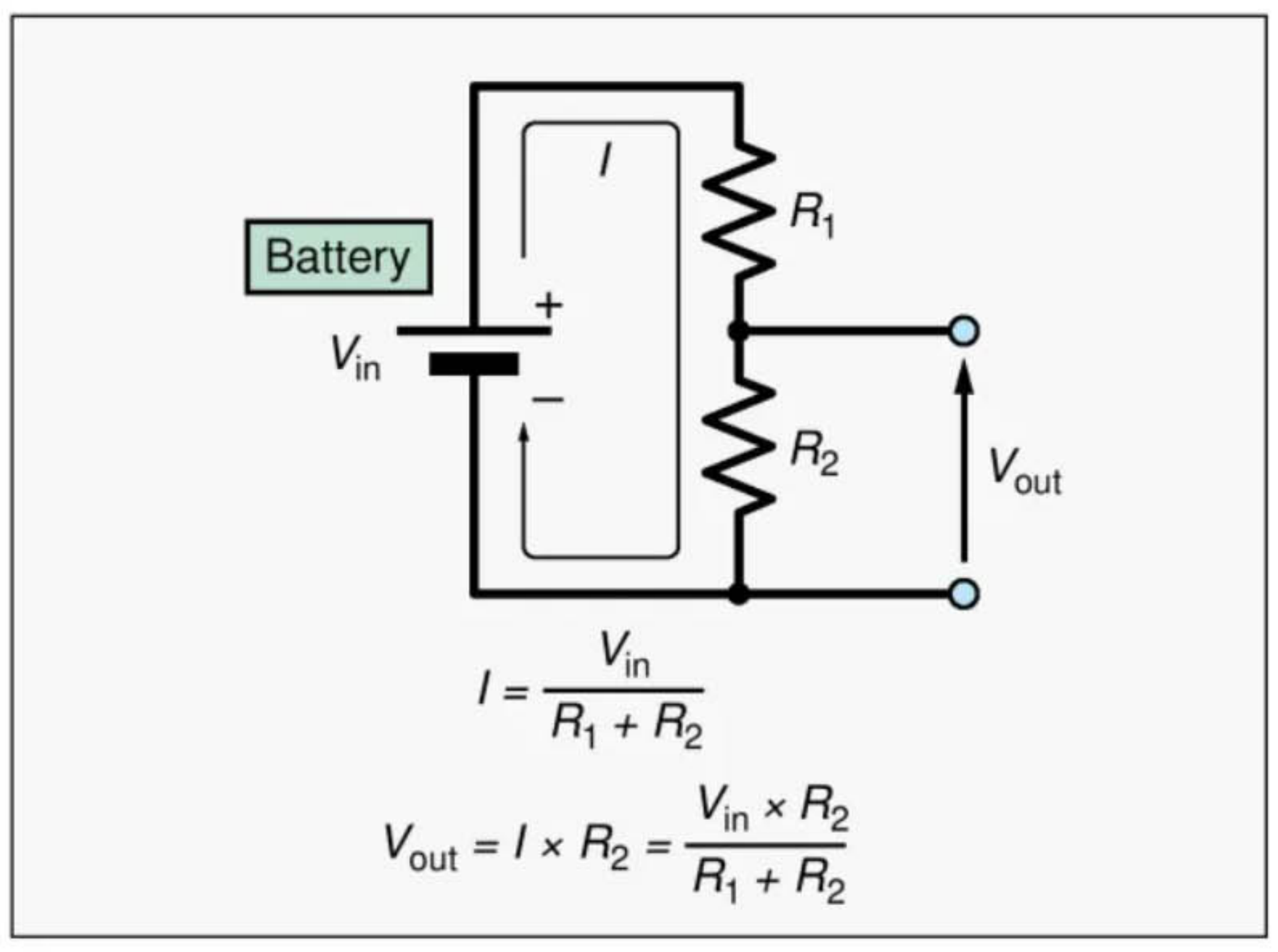


Fig. 5. Potential divider circuit.

$$I = \frac{V}{R}$$

Since the resistors are in series we know the total resistance seen by V_{in} is just $R_1 + R_2$, and thus the current though R_1 and R_2 is:

$$I = \frac{V}{R} = \frac{V_{in}}{R_1 + R_2}$$

Now we need to calculate the voltage across R_2, which is V_{out}; again, we use Ohm's law:

$$V = IR = \frac{V_{in}}{R_1 + R_2} \times R_2 = V_{out}$$

Rearranging a little, we finally get:

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

Notice that if $R_1 = R_2$ then the equation becomes:

$$V_{out} = V_{in} \times \frac{R_2}{R_2 + R_2} = V_{in} \times \frac{1}{2} = \frac{V_{in}}{2}$$

In other words, the input voltage is halved, which is what you would intuitively expect if the two resistors are identical.

If we have particular values of V_{in}, R_1 and R_2 and want to calculate the resulting output voltage (V_{out}) then we just plug in the values. Let's use $V_{\text{in}} = 5.1\text{V}$, $R_1 = 1\text{k}\Omega$ and $R_2 = 4.7\text{k}\Omega$:

$$\begin{aligned} V_{out} &= V_{in} \times \frac{R_2}{R_1 + R_2} \\ &= 5.1 \times \frac{4700}{1000 + 4700} = 4.2V \end{aligned}$$

Notice that since R_2 has a bigger resistance than R_1 the voltage across it (V_{out}) is larger.

Finally, how do you create a potential divider with a particular output for a given input? Let's say you want a divider that gives you one eighth of the input (×1/8, or ×0.125). What this means is that:

$$\frac{R_2}{R_1 + R_2} = \frac{1}{8}$$

If we cross multiply each side we get:

$$8R_2 = R_1 + R_2$$

Leading to:

$$R_1 = 7R_2$$

At this stage there are three things to notice:

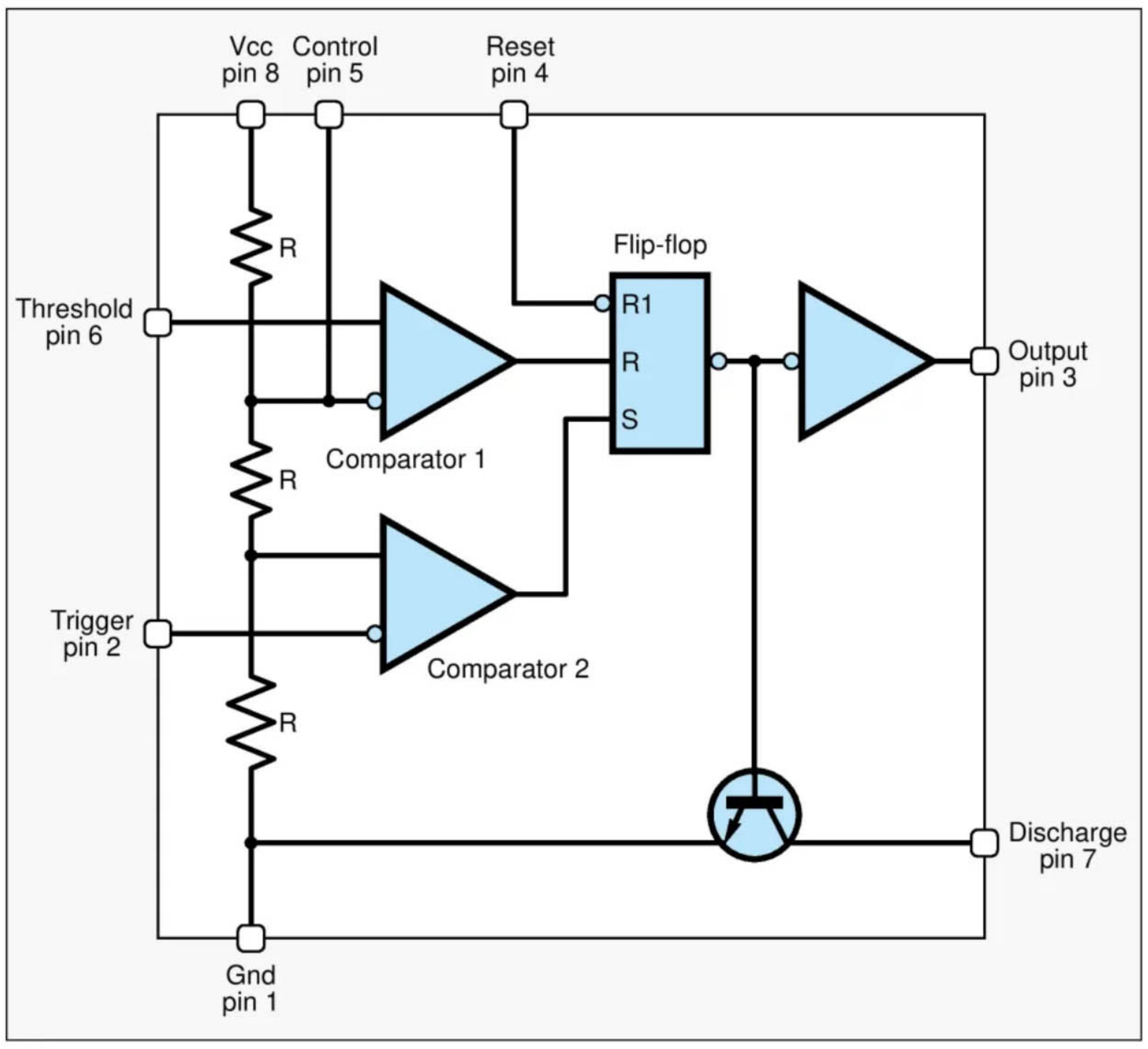
- R_2 is much smaller than R_1, which agrees with our explanation that the bigger or smaller R_2 is compared to R_1 the bigger or smaller will be its proportion of the voltage drop.
- The equation gives the *ratio* of resistor values, not the actual values. You could use 1kΩ and 7kΩ, or 100kΩ and 700kΩ and the result would be the same. This flexibility can be useful.
- Although we wanted a voltage drop to 1/8 of V_{in}, the resistor ratio is 1/7 – this is because the resistor calculation uses $R_2/(R_1+R_2)$, and not R_1/R_2 – you always need to do the actual calculation to find the correct values and don't just assume it's 'obvious'.
- Resistors come in 'funny' values and not always the most convenient steps – for example, while there is a 1kΩ or 100kΩ value, there is no such thing as a 7kΩ or 700kΩ resistor. Often you have to play around with available values to get the ratio you want. For the above example, a good choice would be 1.3kΩ and 9.1kΩ, since:

$$\frac{1300}{1300 + 9100} = \frac{1}{8}$$

It's worth noting that one or both of the elements in a potential divider can be a potentiometer – a variable resistor, which means you can vary the output. Also, you can have as many resistors and outputs as you want, although the analysis can get a bit longwinded. Finally, and this is beyond the scope of this article, you can use other types of components in a potential divider, for example a capacitor, which would let you produce a simple filter. All in all, the potential divider is a very powerful and useful circuit element that is well worth mastering.

If you want to save a little time, you can access the online MitchElectronics potential divider calculator – see: **https://bit.ly/pe-jan24-pdcalc** – but in the long term you really need to be able to do this calculation yourself!

A great use for potential dividers is in sensor circuits, where one of the resistors is replaced with a resistive sensor element. For example, if R_2 is replaced with a PTC (positive temperature coefficient) thermistor whose resistance goes up with an increase in temperature,



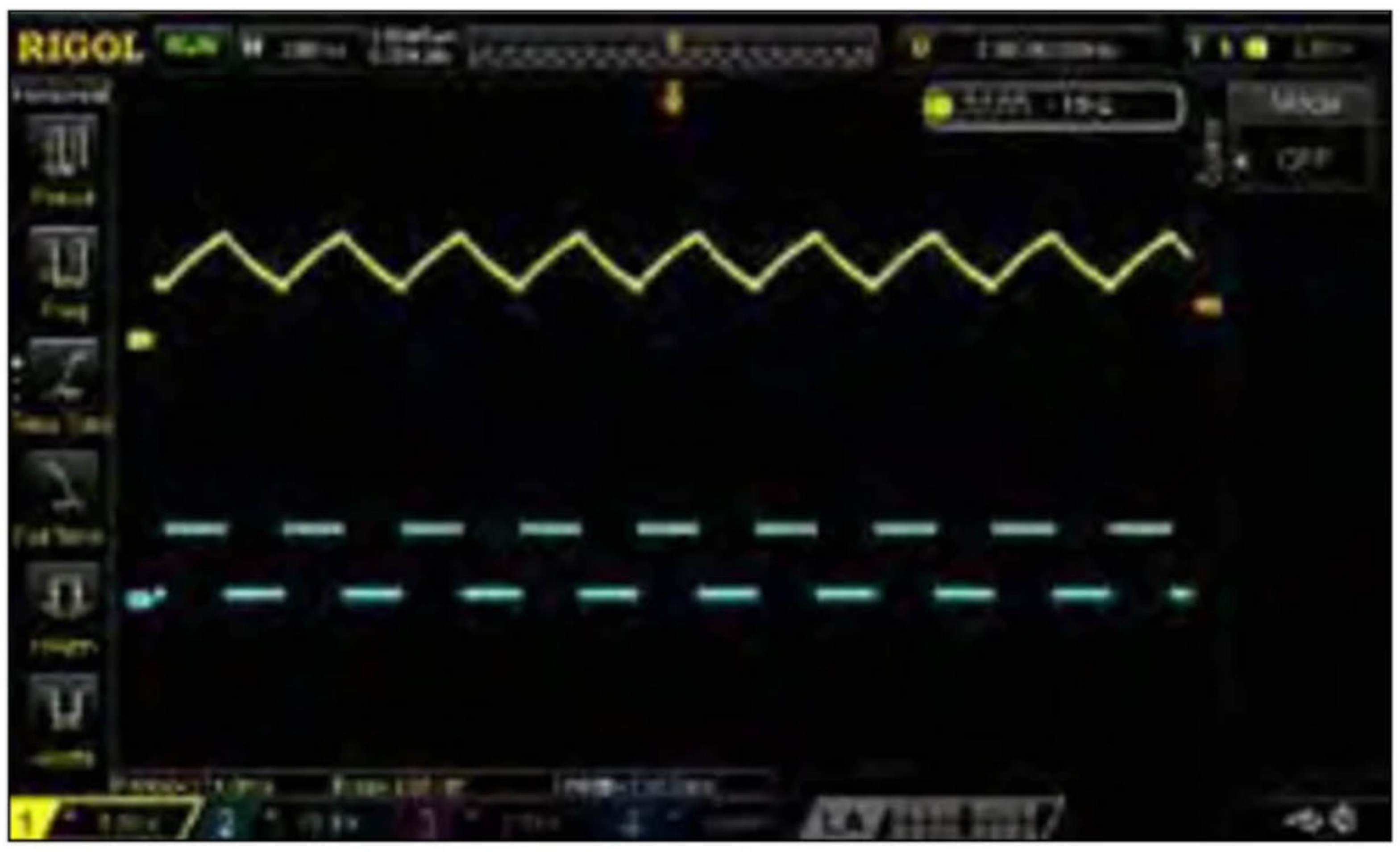


Fig. 6. Schematic of a 555 IC, its RC voltage and output (see last month for more 555 operation details).

then the voltage across the thermistor will increase as its temperature increases.

The same could also be done with a light-dependent resistor (LDR), whose resistance decreases as the intensity of light falling on it increases. In this case, the voltage across the LDR *decreases* as the light intensity *increases*.

Note that most LDRs on the market are based on cadmium, which is a toxic (carcinogenic) material. We recommend avoiding LDRs for light sensors, and instead use a phototransistor and/or photodiode. All MitchElectronics kits that use light sensors use photodiodes, which are safe to use and RoHS compliant.

555 in more detail

Last month we looked at how the 555 IC works, with the capacitor charging and discharging to control the state of the 555. It's important to understand that the the voltage across the capacitor (Fig.6, right), doesn't go right to the power supply and back down to ground, but instead, rises and falls between two trigger points (otherwise known as the trigger and threshold voltages). But how exactly are these voltages defined?

If we look at the inside of the 555 IC (Fig.6, left), you will notice that there are three resistors in series, each having a value of 5kΩ. These three resistors form the potential divider shown in Fig.7, and as we just learned about potentiometers, the voltage drop across each one is proportional to the input voltage. As each resistor is identical, each has a voltage drop across it of 1/3 of the voltage supply.

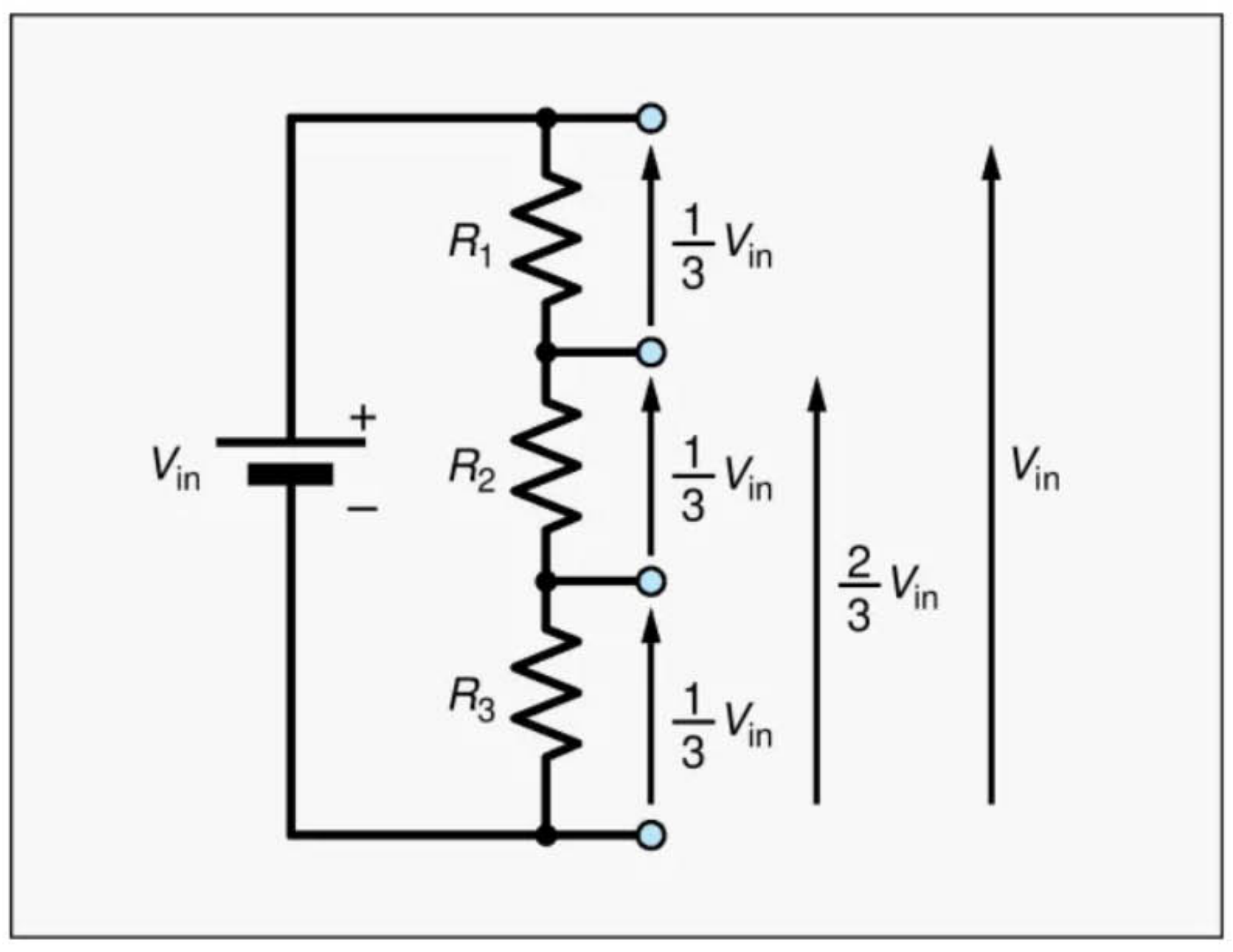


Fig. 7. Voltages across the three internal 5kΩ resistors of a 555 IC.

But, as the sum of these voltages must be equal to the supply voltage (this is a very important rule in electronics), this also means that the voltage at the first resistor is the voltage supply itself, the voltage at the second resistor is 2/3 of the voltage supply, and the last is 1/3 of the voltage supply.

Returning to the 555 internal schematic, the 1/3 and 2/3 voltages are connected to the comparators, this means that our trigger and threshold voltages are 1/3 and 2/3 of the voltage supply. These are the values that the capacitor charges and discharges to. (We haven't met comparators yet, but in essence these are circuit elements that 'compare' two voltages and their output goes high or low depending on which of their two inputs is bigger.)

Introduction to logic

So far, we have looked at circuits whose voltages and currents have been *continuous*, meaning that over a range, they could be any value: 1V, 5V, 2.384V, or for current 1A, 0.659A… and so on. In the field of electronics, such continuous values are thought of as 'analogue', which is how analogue electronics gets its name. Fig.8 shows a continuous, analogue signal.

However, in *digital* electronics, voltages only have one of two discrete states – high or low – also called on/off, 1/0 or true/false respectively. As these values can only be one of two different states, they are said to be 'binary', and this is why binary numbers (base 2) and binary arithmetic are so easily used in electronics. Fig.9 shows a digital signal; you can see it only take two values and is hence binary in nature.

In our 555 astable and monostable circuits, the voltage across the timing capacitor varies throughout time, and it is this continuous range of possible values that makes this capacitor voltage analogue. However, the output of the 555 IC is either high (VCC) or low (0V), and hence, we call the output digital. Because the 555 timer IC has both analogue and digital components, it is referred to as being a 'mixed-signal' IC.

What are CMOS ICs and the 4000 Series?

So far, we have only looked at one IC, the 555 timer, a mixed-signal device dealing with both analogue and digital voltages. However, many ICs only deal with digital signals. These range from very simple devices up to the most sophisticated microprocessors. At the 'simple' end we have logic devices that process digital signals with simple functions, often called 'gates', or sub-systems built up from gates, such as counters.

Arguably, the two most famous families of logic devices are the 7400 and 4000 series. The older of the two, the 7400, was initially brought out in 1966 by Texas Instruments to help engineers reduce the

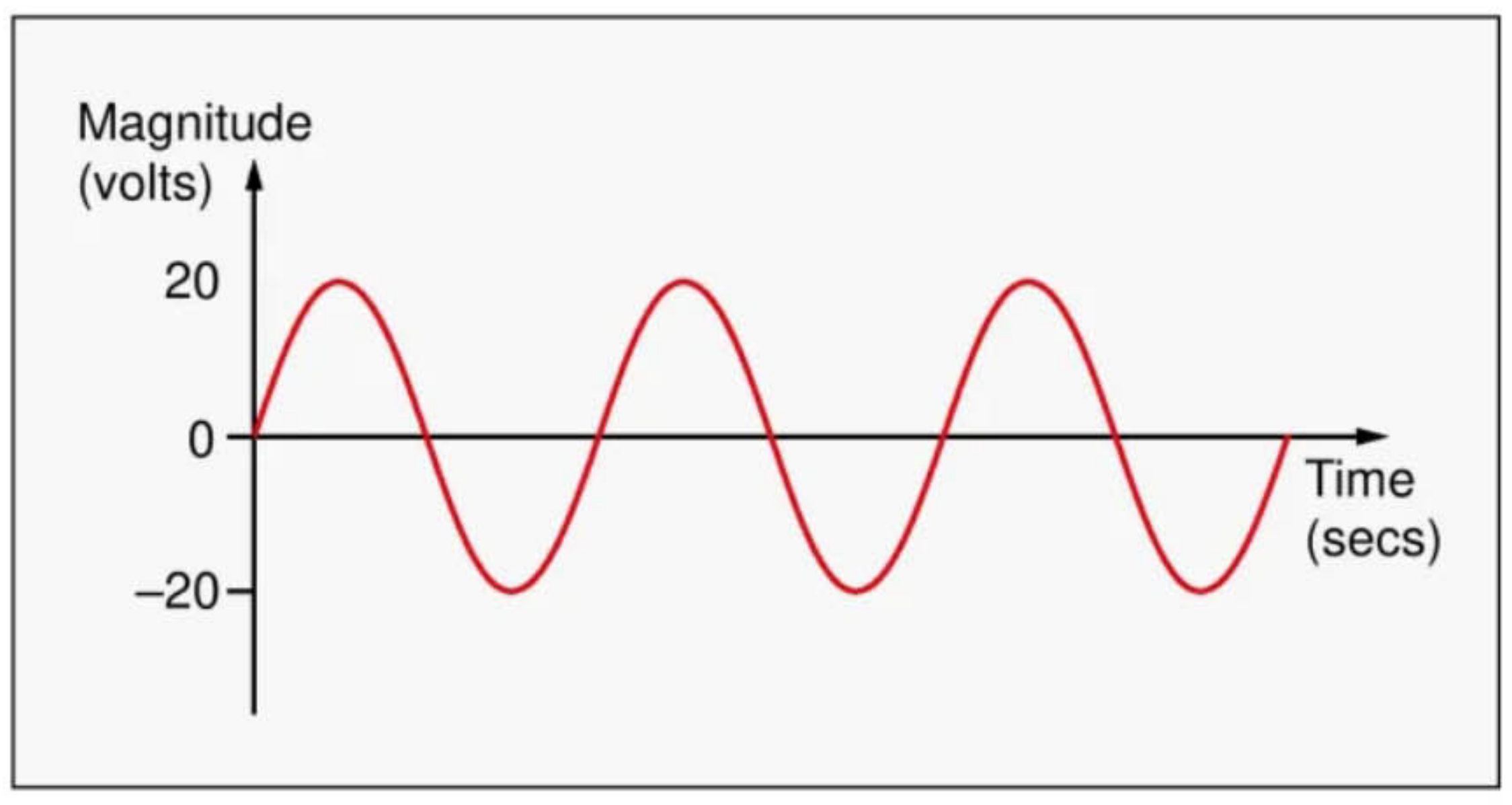


Fig. 8. Example of an analogue signal.

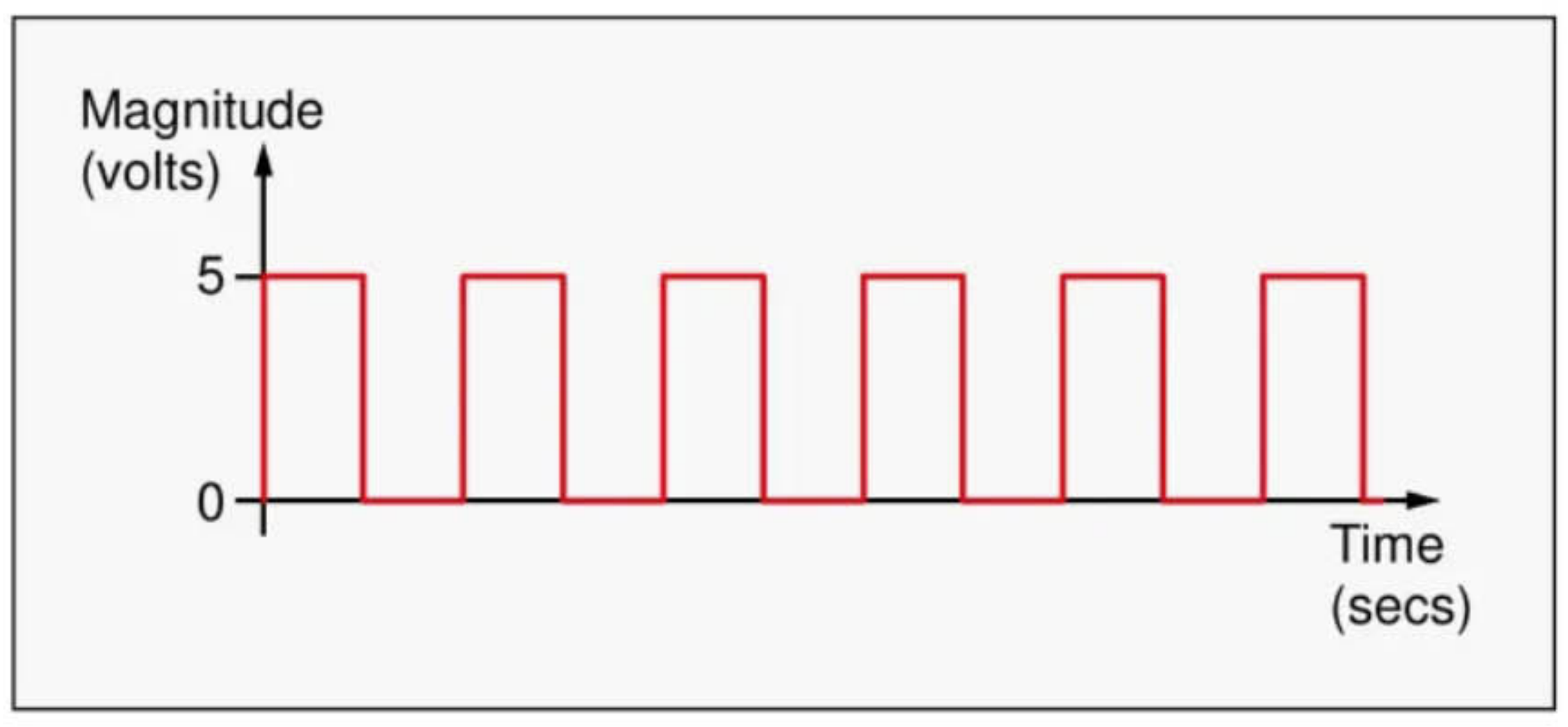


Fig. 9. Example of a digital signal.

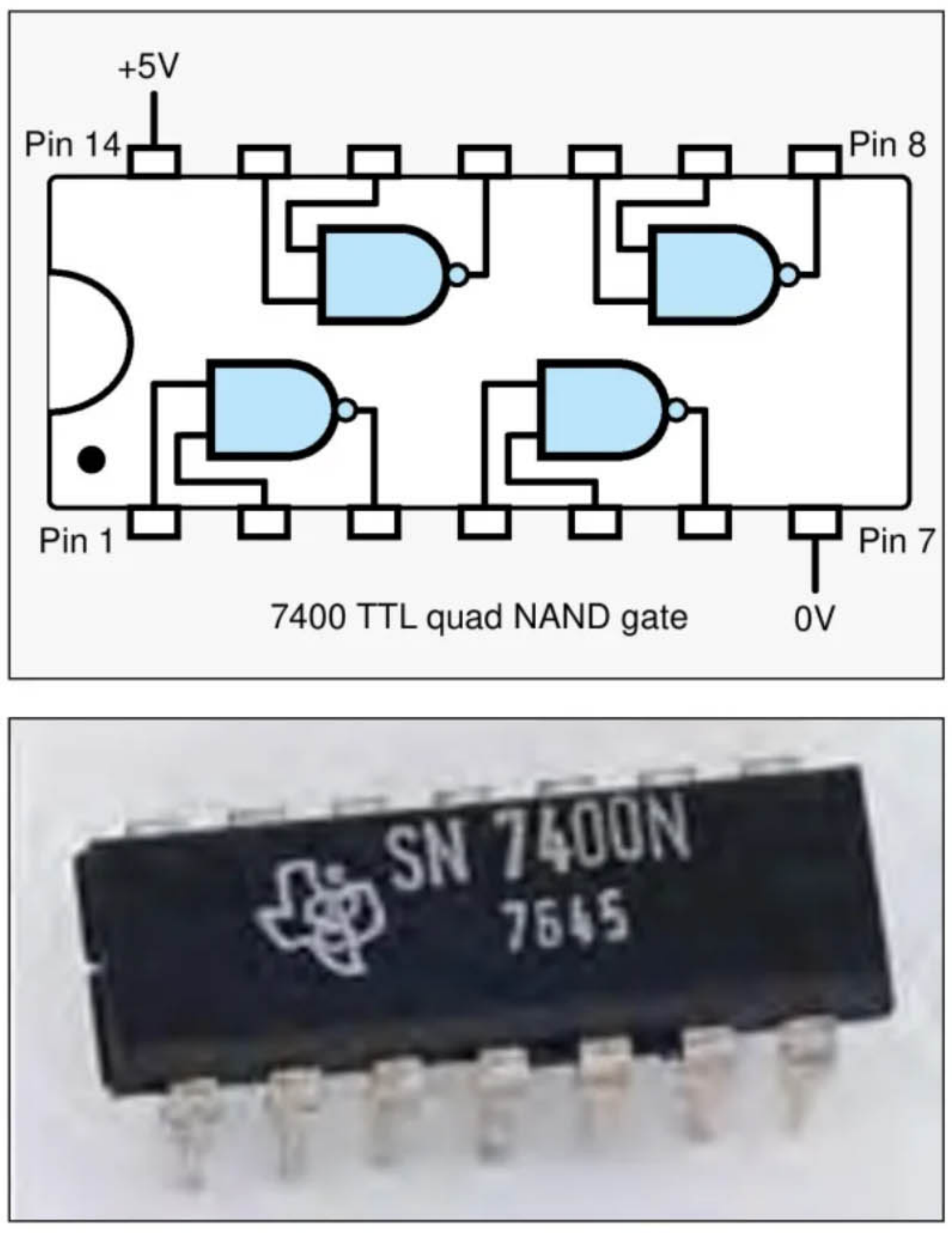


Fig. 10. Example of a 7400N and its internal gates.

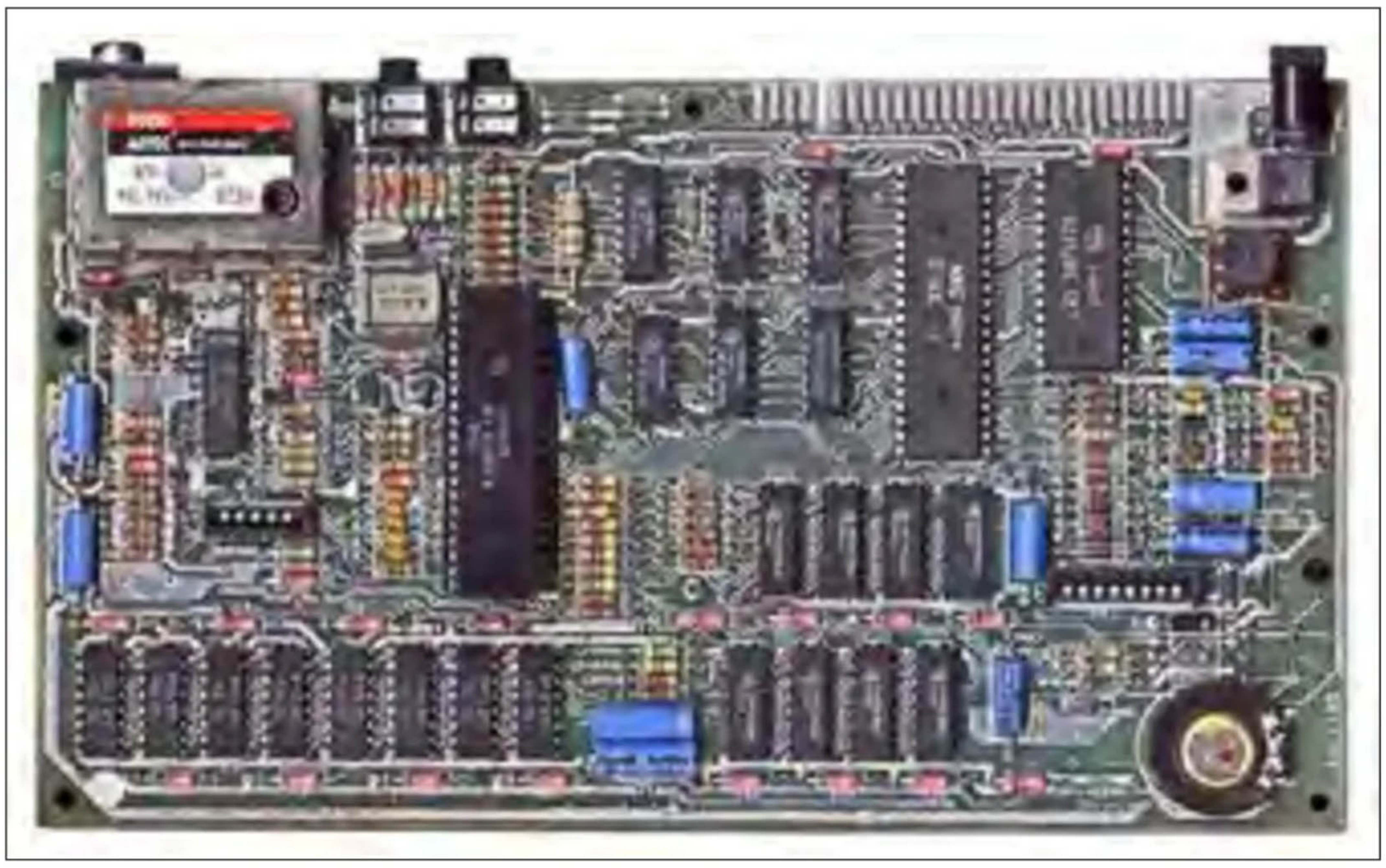


Fig. 11. Most computing systems from the 1980s used ICs from the 7400 and 4000 series of logic devices. This photo shows the motherboard of a Sinclair ZX Spectrum.

number of components on circuit boards by integrating logic circuits into silicon chips. The popularity of these chips was so massive that the 7400 quickly accounted for over 50% of the logic market shortly after being released to the public. Fig,10 shows a typical 14-pin DIL 7400-series IC; in this case a quad NAND gate chip.

The 7400 series used energy-hungry design techniques (called TTL), which where fast but consumed a large amount of current. Recognising this problem, RCA developed the 4000 series of logic chips which used the much more energy-efficient CMOS technology.

While the first CMOS devices were much slower compared to their TTL counterparts, the fact that they consumed far less power made them ideal for low-power environments – for example, battery-powered applications. Eventually, as CMOS technologies improved, not only did CMOS logic devices come to match the speed of TTL, but rapidly surpassed it and became the dominant logic technology that is now used throughout electronics. In fact, CMOS technology was so beneficial to engineers that many 7400 series devices now have CMOS variants.

Despite the intense battle between the 7400 series and the 4000 series, both have proven to be extremely capable, and can even be mixed and used in the same circuit. While some chips in both families have been discontinued, the most important ones are still in active production.

The 4000 series of logic chips consist of a large range of ICs that cover the most essential logic devices, including logic gates, counters, shift registers, and multiplexers. These components can be combined to build more complex circuits, with early computers being made almost out entirely of 4000 series devices. Even as late as the 1980s it was common to see plenty of these handy ICs supporting microprocessor-based PCs. However, considering that most electronic designs have now moved towards complex microcontrollers and microprocessors, nowadays it is rare to see circuits using more than one or two 4000 series devices.

What makes the 4000 series especially handy to makers is that they are all

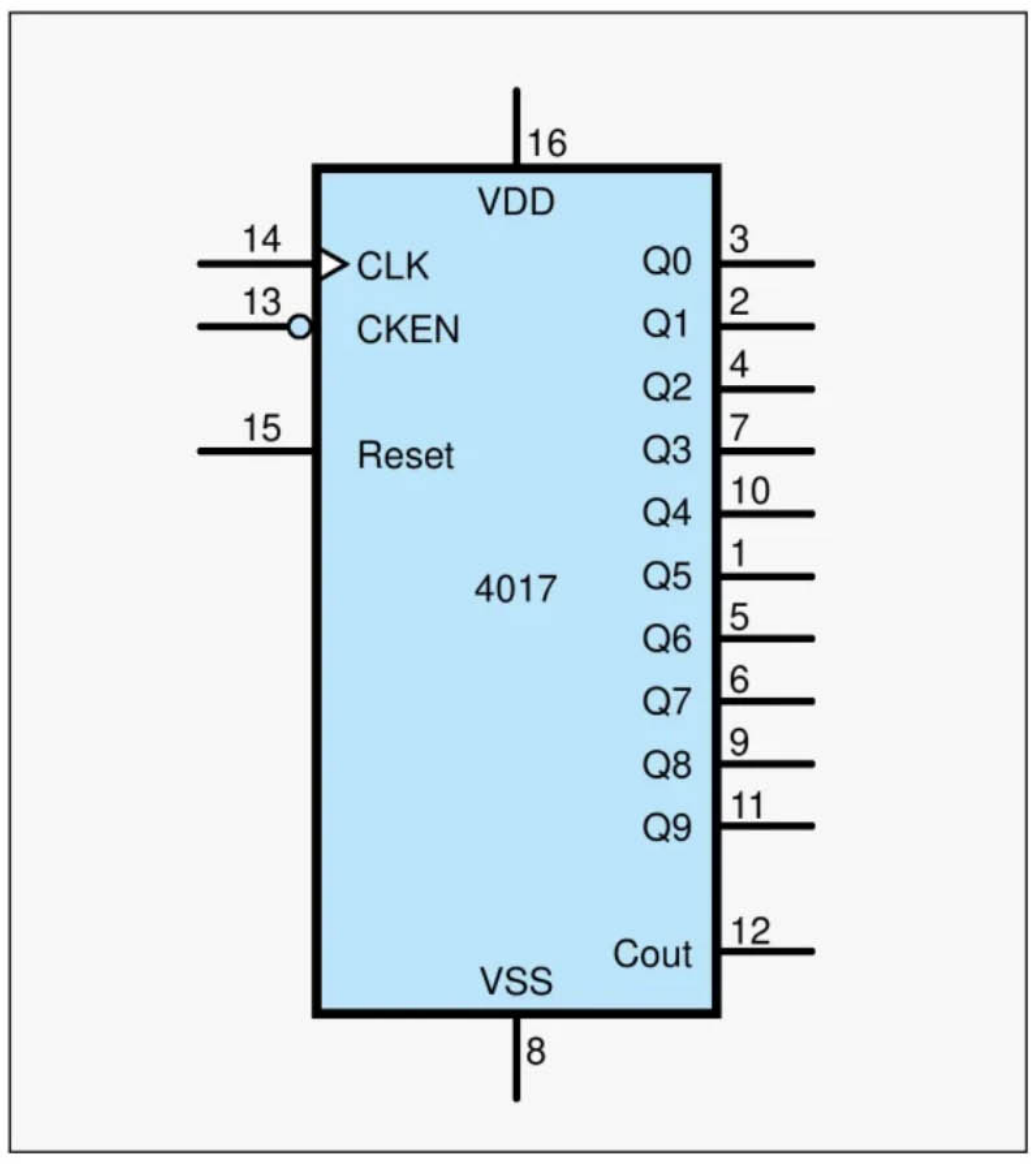


Fig. 12. 4017 counter and its schematic circuit symbol.

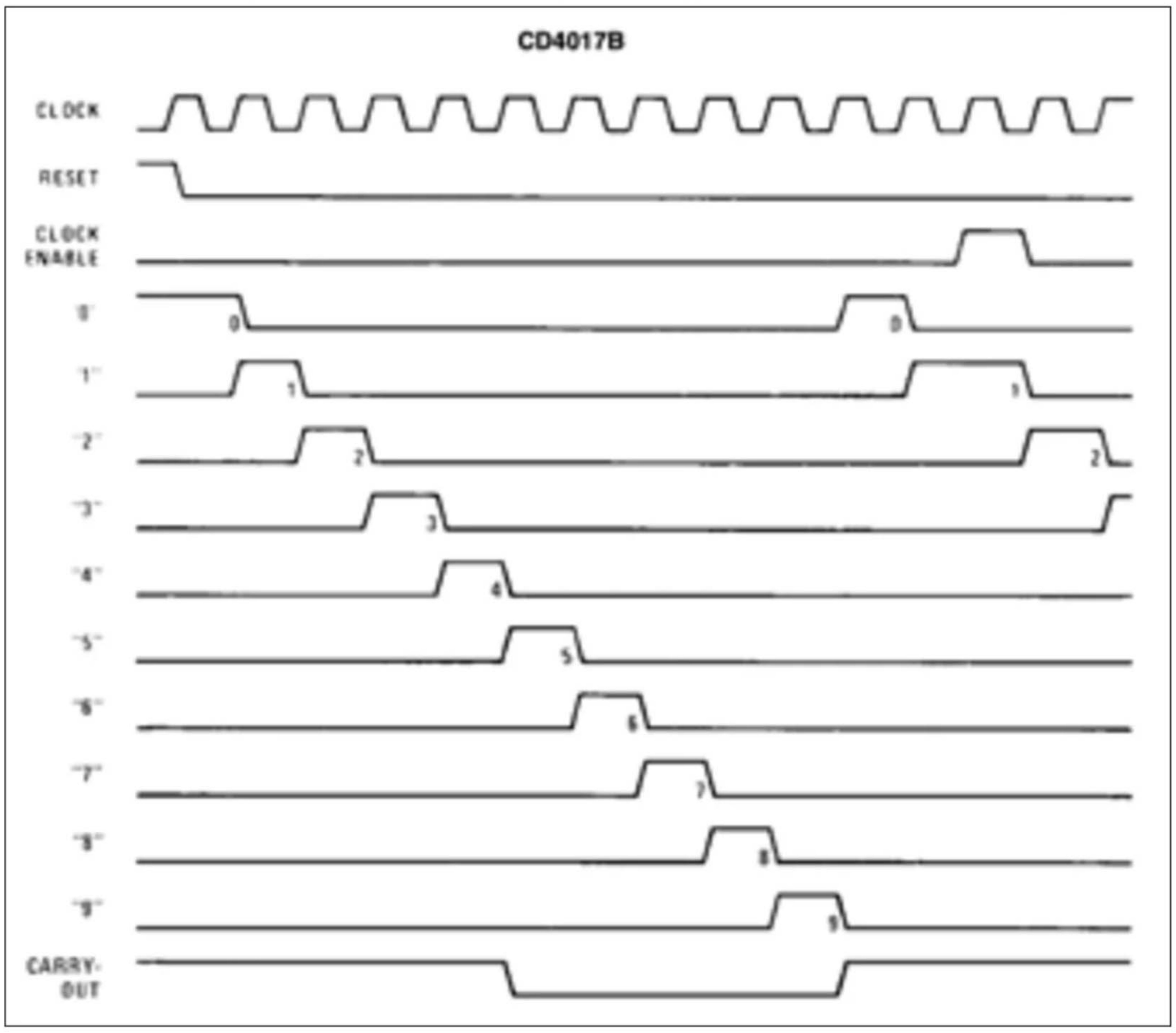


Fig. 13. 4017 output count graph.

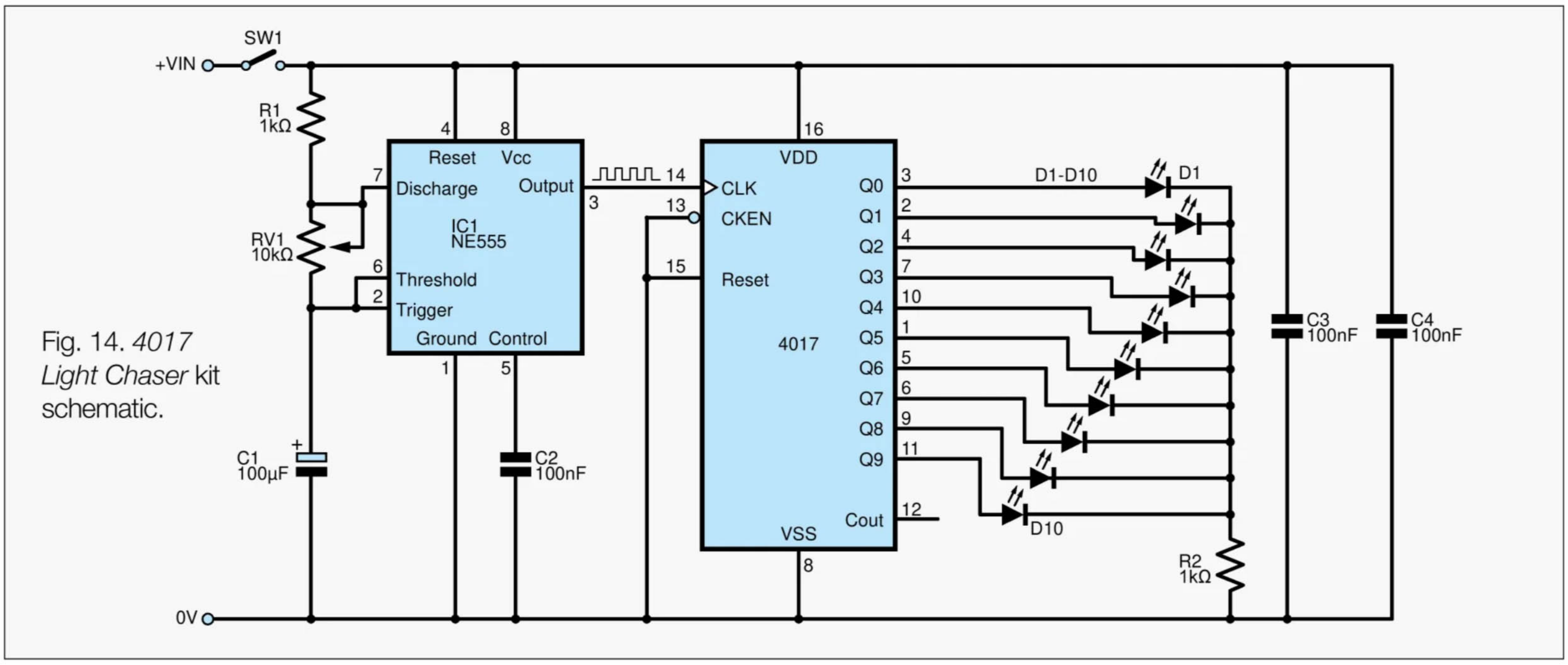

SW1
+VIN
R1
1kΩ
RV1
10kΩ
C1
100µF
0V
4
8
7
6
2
1
5
3
Reset
Vcc
Discharge
Output
IC1
NE555
Threshold
Trigger
Ground
Control
C2
100nF
14
13
15
16
VDD
CLK
CKEN
Reset
4017
VSS
8
Q0
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Cout
12
D1-D10
D1
D10
R2
1kΩ
C3
100nF
C4
100nF

Fig. 14. *4017 Light Chaser* kit schematic.

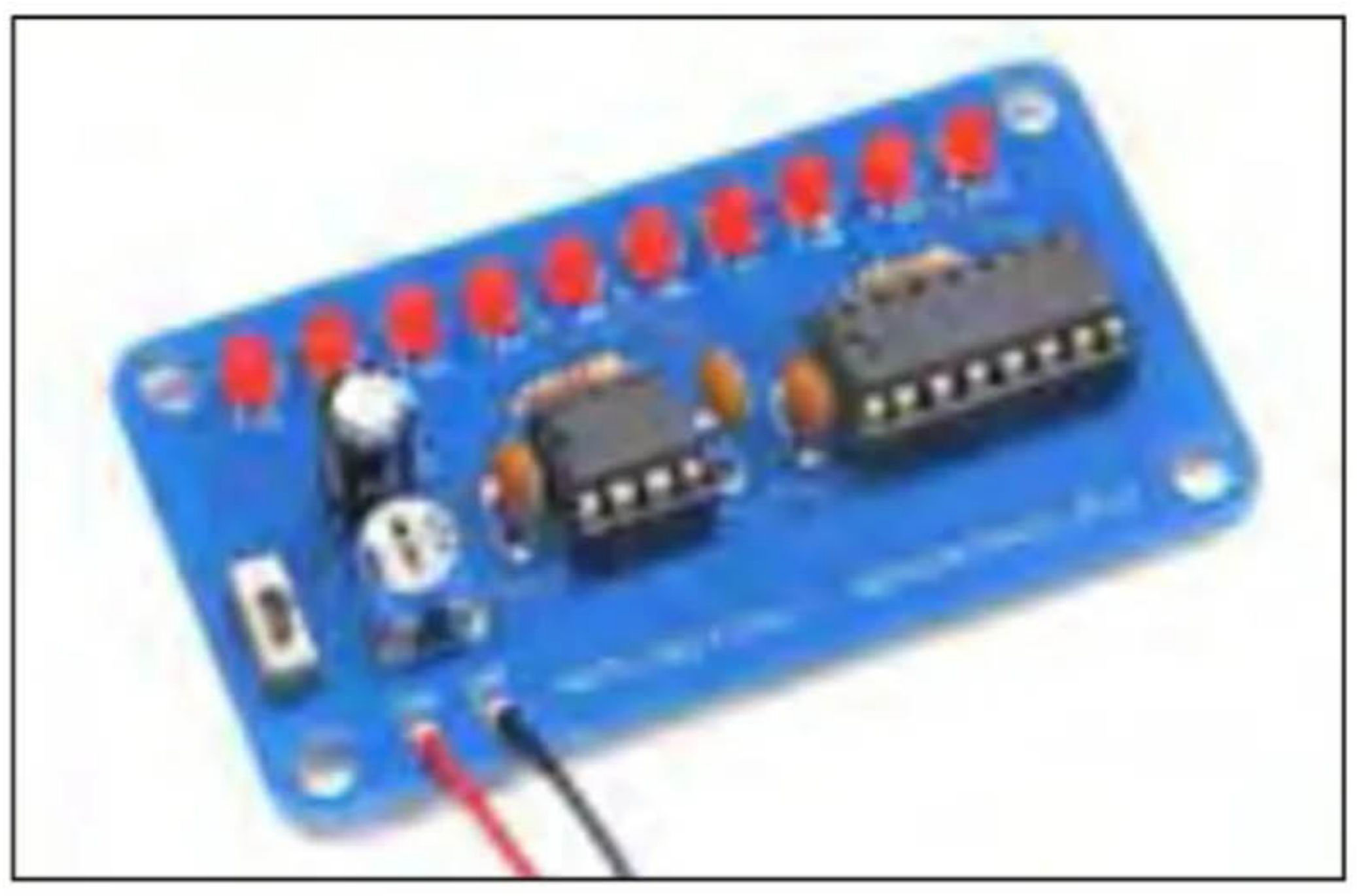


Fig. 15. Assembled *4017 Light Chaser* kit.

available in through-hole DIP packages, which can be used with breadboards, stripboards and simple PCBs. Thus, not only can they be used in prototyping, but also they can be reused in future circuits/projects.

Special note on using 4000 series devices – it is important to keep in mind that the 4000 series is based on CMOS technology, which is extremely sensitive to static electricity. Therefore, it is vital when using these chips that static electricity is removed from your body, your project and workstation. This can be done by touching a grounded piece of pipe on a radiator, or better still, investing in an inexpensive grounded antistatic work mat and wristband.

What is the 4017 IC?

The first 4000 series IC that we will be introduced to is the 4017 10-stage Johnson counter. It's schematic representation is shown in Fig.12. This IC is used to create all kinds of lighting effects – for example a light chaser, where an illuminated LED appears to move across a series of LEDs.

The 4017 10-stage Johnson counter is a counter with ten stages, a clock input pin, a clock disable pin, and a reset pin. It is built with a 5-stage binary counter connected to an output decoder to produce the 10-stage output. The 4017 can also be described as a 'decade' counter, which means it counts to ten using the numbers 0 to 9. The counter increases with one for every rising clock pulse. After the counter has reached 9, it starts again from 0 with the next clock pulse.

Fig.13 shows how each *rising* (low-to-high) edge of the clock input (where the signal goes from low to high), results in the counter incrementing by one, and the next output stage turning on. Once the counter has reached its maximum count of 9, a final clock signal will reset the counter to 0.

The reset pin to the 4017 IC is used to reset the current state of the counter to 0 if the reset pin is set to a high state. The 4017's disable pin set to a high state prevents the clock from incrementing the counter.

Logic ICs need a power supply, usually referred to as VDD and VSS, where VDD is connected to a positive supply (such as 9V for CMOS), and VSS is connected to the negative supply, typically 0V.

The 4017 Light Chaser

The *4017 Light Chaser* kit from MitchElectronics is our most basic 4017 circuit, and not only demonstrates how the 4017 IC works, but also how to use the 555 astable as a clock source. Its schematic is show in Fig.14 and a completed kit in Fig.15. The speed of oscillation of the 555 astable is

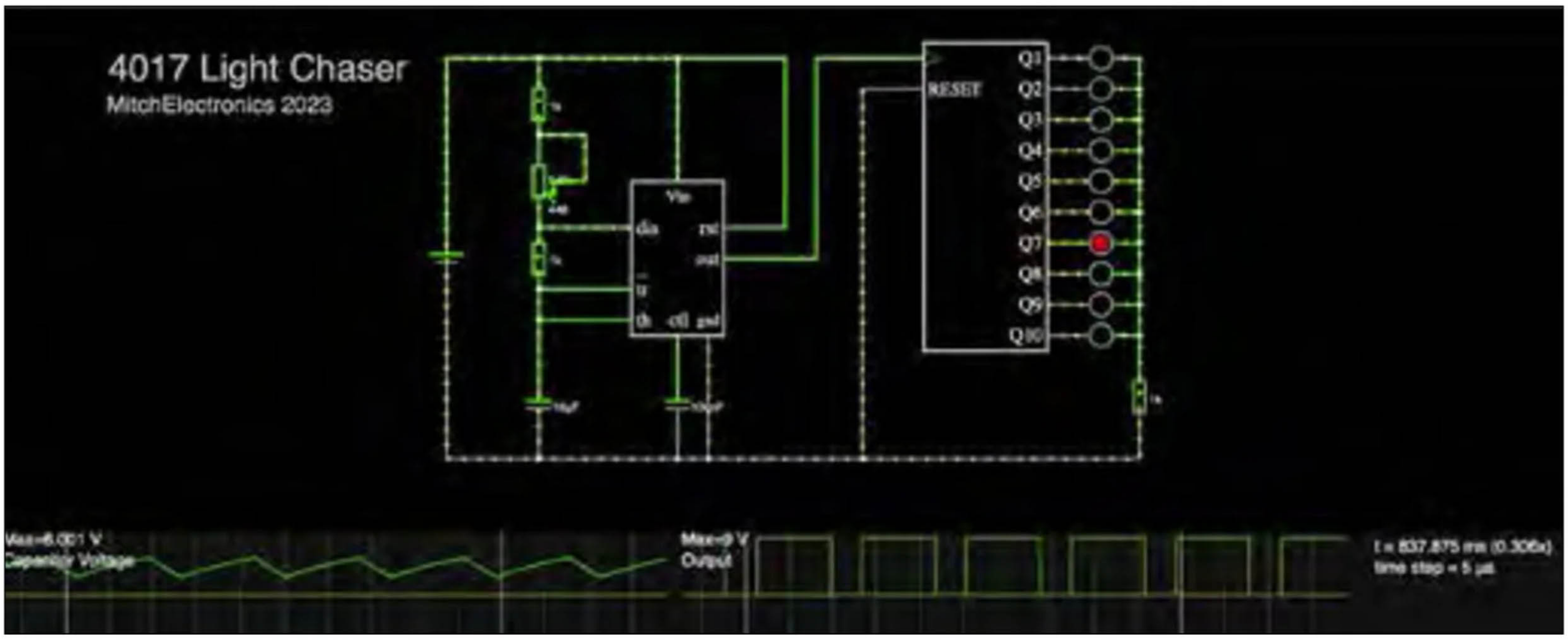

4017 Light Chaser
MitchElectronics 2023
RESET
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
Q10
Capacitor Voltage
Output

Fig. 16. *4017 Light Chaser* simulation.

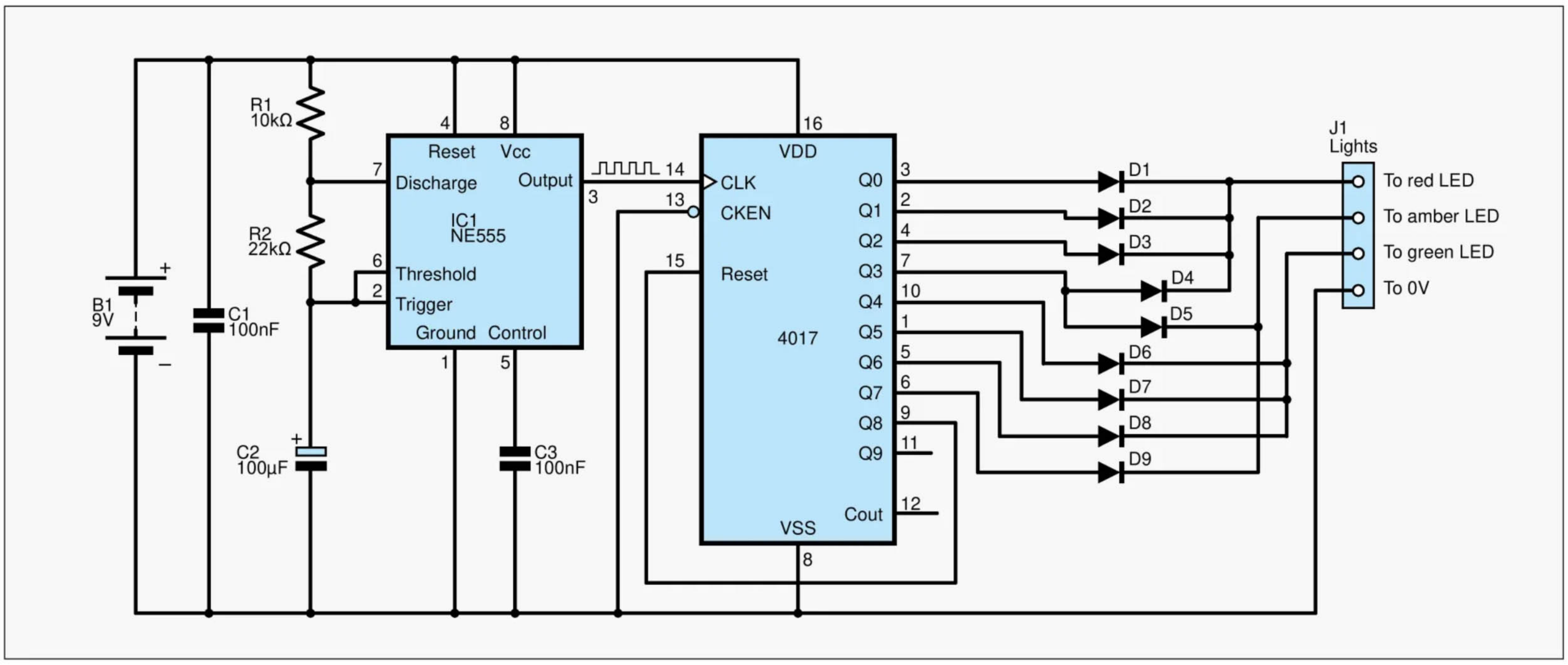
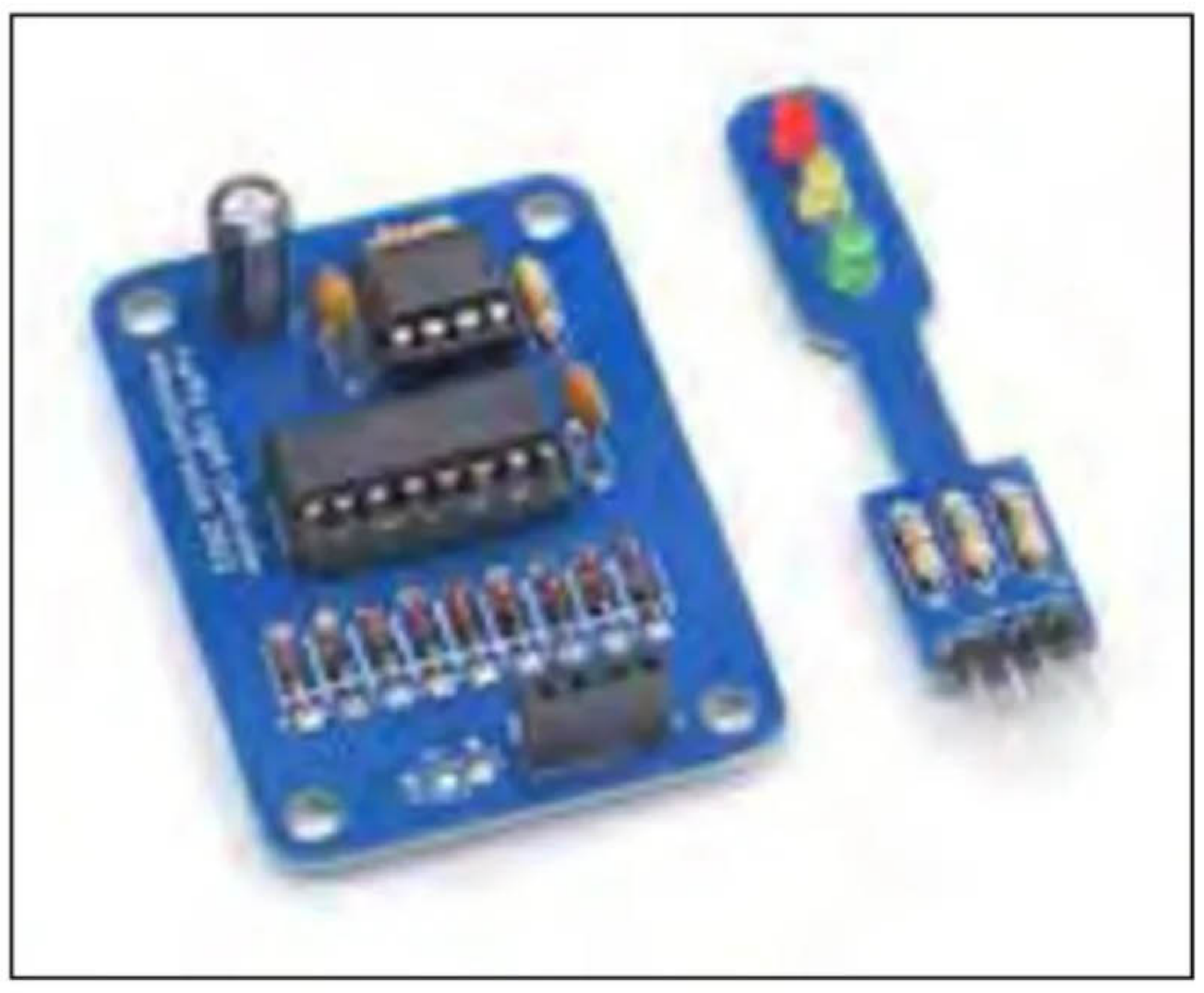


Fig. 17. (Above) *Traffic Light* schematic and (below) completed project kit.



determined by the timing capacitor C_1, the resistor R_1 and the potentiometer RV1. If the value of RV1 is low, then the 555 astable will oscillate quickly, and if the value of RV1 is high, then the 555 astable will oscillate more slowly.

The output of the 555 astable is connected to the clock input of the 4017 IC, and both the clock disable and reset pin are connected to 0V, meaning that they are not used / never operating in this circuit. Each output of the 4017 is connected to its own LED, and each LED shares a single resistor, R_2. Only one output from the 4017 will ever be high/on, so only one LED will ever be illuminated, thus each LED takes turn in using resistor R_2.

Each clock pulse from the 555 astable makes the 4017 IC increments its internal counter, resulting in the next LED in the chain to shine. After ten clock pulses, the 4017 IC resets its count, shining the first LED in the chain, and repeating the cycle forever. For those who want to see a working simulation of this kit (as shown in Fig.16) head over to the *4017 Light Chaser* Instruction page and use the in-browser Falstad Circuit Simulation, which allows you to adjust the *4017 Light Chaser* frequency in real-time: **https://mitchelectronics.co.uk/resources/simulator/**

SMD version

The *4017 Light Chaser* uses through-hole components, which are easy to solder for beginners, but for those who want to practise their skills at soldering, then the *4017 Light Chaser* SMD Trainer kit offers the same *4017 Light Chaser* circuit but using only SMD parts. The kit uses 0805-sized resistors and capacitors, a small potentiometer, and a 555 and 4017 in SOIC SMD packages.

Traffic Light

The *Traffic Light* kit is very similar to the *4017 Light Chaser* in that it uses a 555 astable connected to a 4017 IC. However, there are a few differences that make it behave differently: specifically, the astable itself and the output stage of the 4017.

Unlike the *4017 Light Chaser*, the *Traffic Light* doesn't have a potentiometer to change the speed of the astable, and the use of larger timing resistors (R_1 and R_2) results in a rather slow frequency (less than 0.5Hz). On the output side of the 4017 IC, outputs 0, 1 and 2 are connected to the red LED of the traffic light, output 3 is connected to both the red and amber LED, outputs 4, 5 and 6 are connected to the green LED, and output 7 is connected to the amber LED. Finally, output 8 is connected to the reset pin, so that when the counter reaches the ninth count, it automatically resets back to output 0.

Now, you may have noticed from the schematic in Fig.17 that each output of the 4017 IC is connected to a diode, and there is a very important reason for this. CMOS logic devices have outputs that are either connected to the positive power supply or the negative supply. If a CMOS output is connected directly to one of the power rails, then it becomes possible for a large current to flow either in or out of the CMOS output, which will damage or destroy the device.

The purpose of the diodes is to allow multiple outputs to be connected without risking current flowing back into the 4017. For example, in the case of the first state (where output 0 is high), the diode D1 becomes forward biased, and therefore can conduct electricity.

However, because outputs 1 and 2 are low, their associated diodes D2 and D3 are not forward biased, and therefore do not conduct electricity. This prevents electricity from output 0 traveling back into outputs 1 and 2, which would damage the 4017 IC.

Simply put, current can flow out of the outputs and into the LEDs, but current cannot flow back into the 4017 IC. The resulting pattern that the *Traffic Light* exhibits is the standard UK traffic light sequence, with red being followed by red plus amber, then green, then amber alone, and finally back to red – see Fig.18.

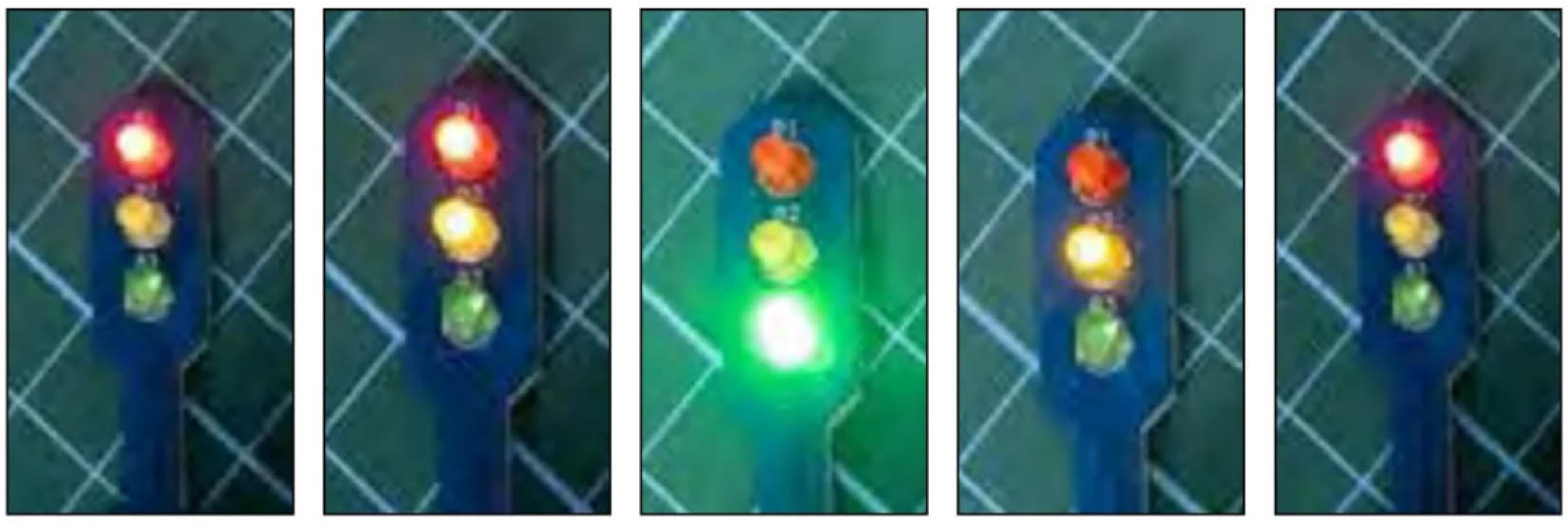
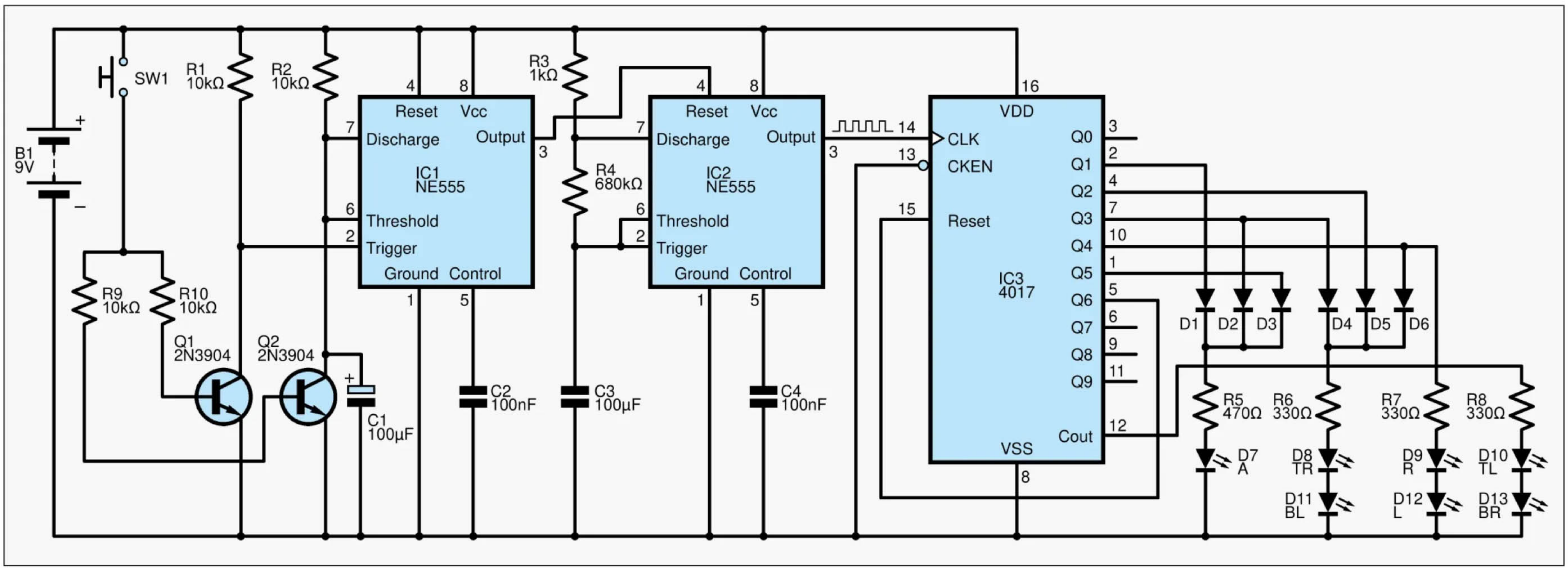


Fig. 18. LED sequence of the *Traffic Light* kit.


B1
9V
+
–
SW1
R1
10kΩ
R2
10kΩ
R9
10kΩ
R10
10kΩ
Q1
2N3904
Q2
2N3904
C1
100µF
+
4
8
Reset
Vcc
7
Discharge
Output
3
IC1
NE555
6
Threshold
2
Trigger
Ground
Control
1
5
C2
100nF
R3
1kΩ
R4
680kΩ
C3
100µF
IC2
NE555
C4
100nF
14
CLK
13
CKEN
15
Reset
16
VDD
IC3
4017
VSS
8
Cout
12
Q0
Q1
Q2
Q3
Q4
Q5
Q6
Q7
Q8
Q9
3
2
4
7
10
1
5
6
9
11
D1
D2
D3
D4
D5
D6
R5
470Ω
R6
330Ω
R7
330Ω
R8
330Ω
D7
A
D8
TR
D9
R
D10
TL
D11
BL
D12
L
D13
BR

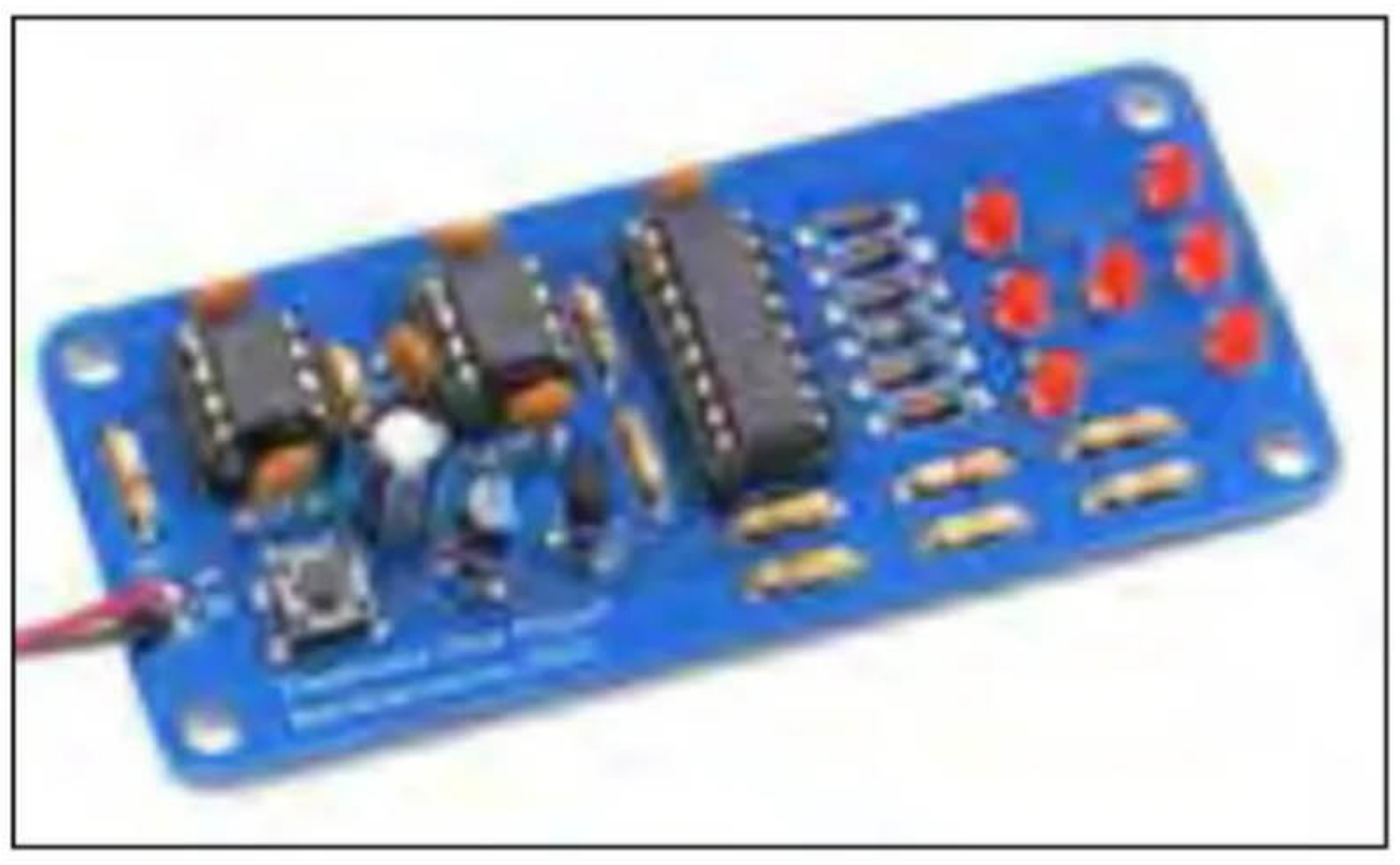


Fig. 19. *Electronic Dice* schematic and kit.

Electronic Dice

The *Electronic Dice* kit combines one 555 astable, one 555 monostable and a 4017 IC to create an electronic dice that simulates a dice roll – see schematic in Fig.19. (Revisit *Part 1* last month for a refresher on how the 555 astable and monostable operate.) Upon pushing the roll button, the dice begins a rolling animation, and after a predetermined length of time, will stop on a value between 1 and 6, with the LED pattern showing the dice face.

In order for this kit to work, the first stage in the circuit is a 555 monostable, which is triggered upon pressing the roll button. The high time of this monostable is determined by resistor R_2 and capacitor C_1, and as there are no potentiometers, this time length is fixed. However, a transistor Q2 is also connected to the roll button, which, when pushed, keeps the capacitor C_1 discharged. This is useful for allowing the user to maintain the roll action for as long as is needed by holding onto the button (similar to keeping the dice rolling in one's palm).(We haven't discussed transistors in any detail in this series yet, but for now you can think of the transistor here as simply an electronically controlled switch that applies a short-circuit across the capacitor.)

The second stage of the *Electronic Dice* is a 555 astable, whose reset input is connected to the output of the 555 monostable. Before the roll button is pushed, the output of the 555 monostable is low, meaning that the 555 astable is kept in reset, and thus, doesn't oscillate. When the roll button is pushed, the output of the 555 monostable goes high, and this reslults in the 555 astable starting to oscillae. The output of the 555 astable is connected to the 4017 IC clock input, so the 4017 begins to count while the output of the 555 monostable remains high.

The output of the 4017 IC is connected to a complex arrangement of diodes and resistors that generate the six different faces of a dice (Fig.20). Determining the logic pattern of each dice face is beyond the scope of this article but may be revisited in future articles when we cover logic and truth tables.

Eventually, the 555 monostable's output goes low, and this not only stops the 555 astable oscillator, but also prevents further counting of the 4017 IC. Thus, the dice face is fixed, and this indicates the face the electronic dice shows.

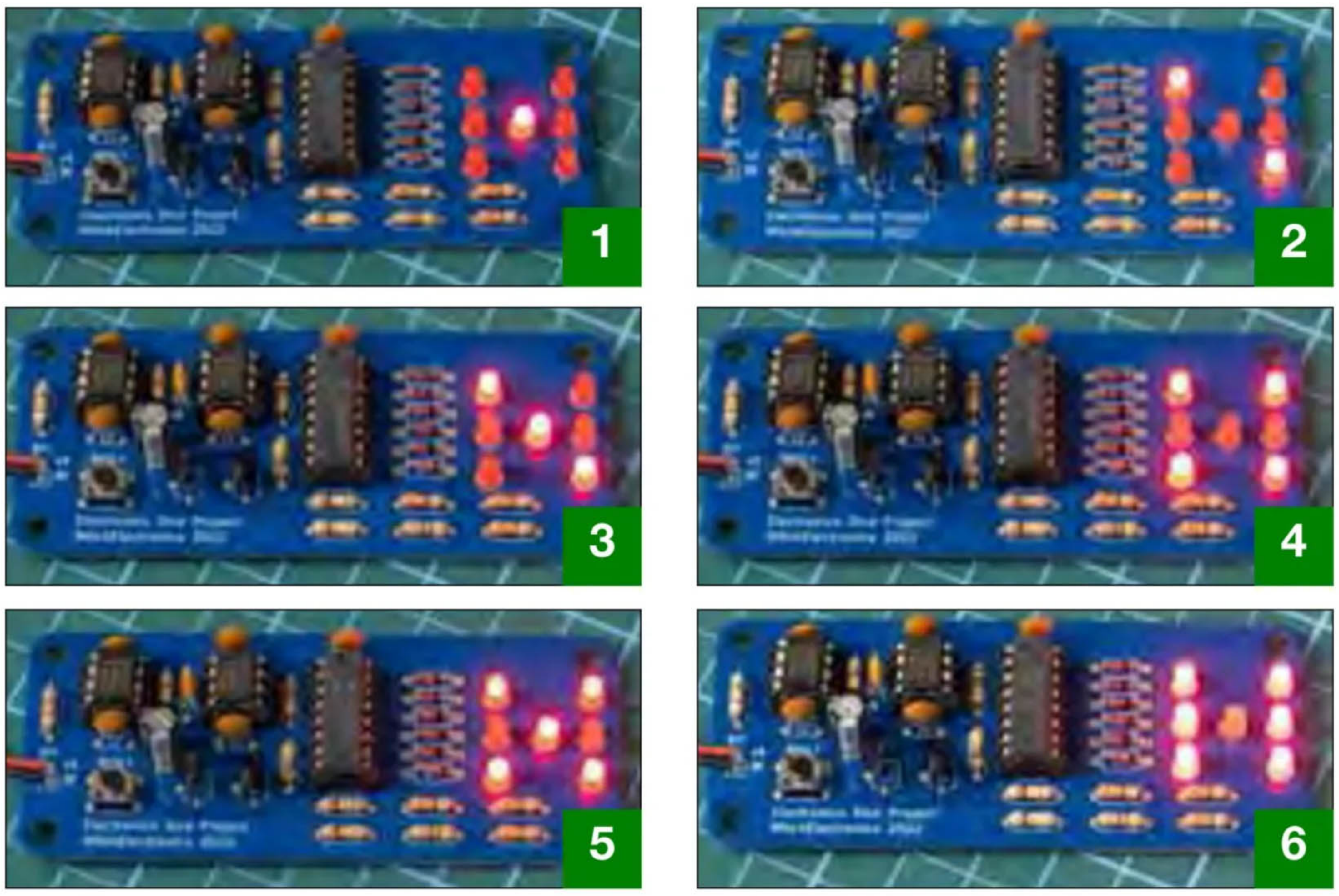


Fig. 20. Image sequence of the *Electronic Dice*: 1 to 6 (top left to bottom right)

Build advice

For a full explanation and example of building a MitchElectronics kit, see the December 2023 issue of *Practical Electronics*, where we cover the challenges involved with soldering and what order parts need to be soldered in.

A quick build and assembly recap is demonstrated in Fig.21: it is always good to solder small parts first, with the most bulky and awkward components being soldered in last. It is essential that the polarisation/orientation of parts is checked, including ICs, electrolytic capacitors and diodes. In MitchElectronics kits, the anode of a diode is indicated by the circular pad, while for electrolytic capacitors, it is a square pad – see Fig.22.

For a full guide on how to solder both through-hole and SMD parts, you can check out the MitchElectronics soldering guide, which can be found at: **https://mitchelectronics.co.uk/resources**

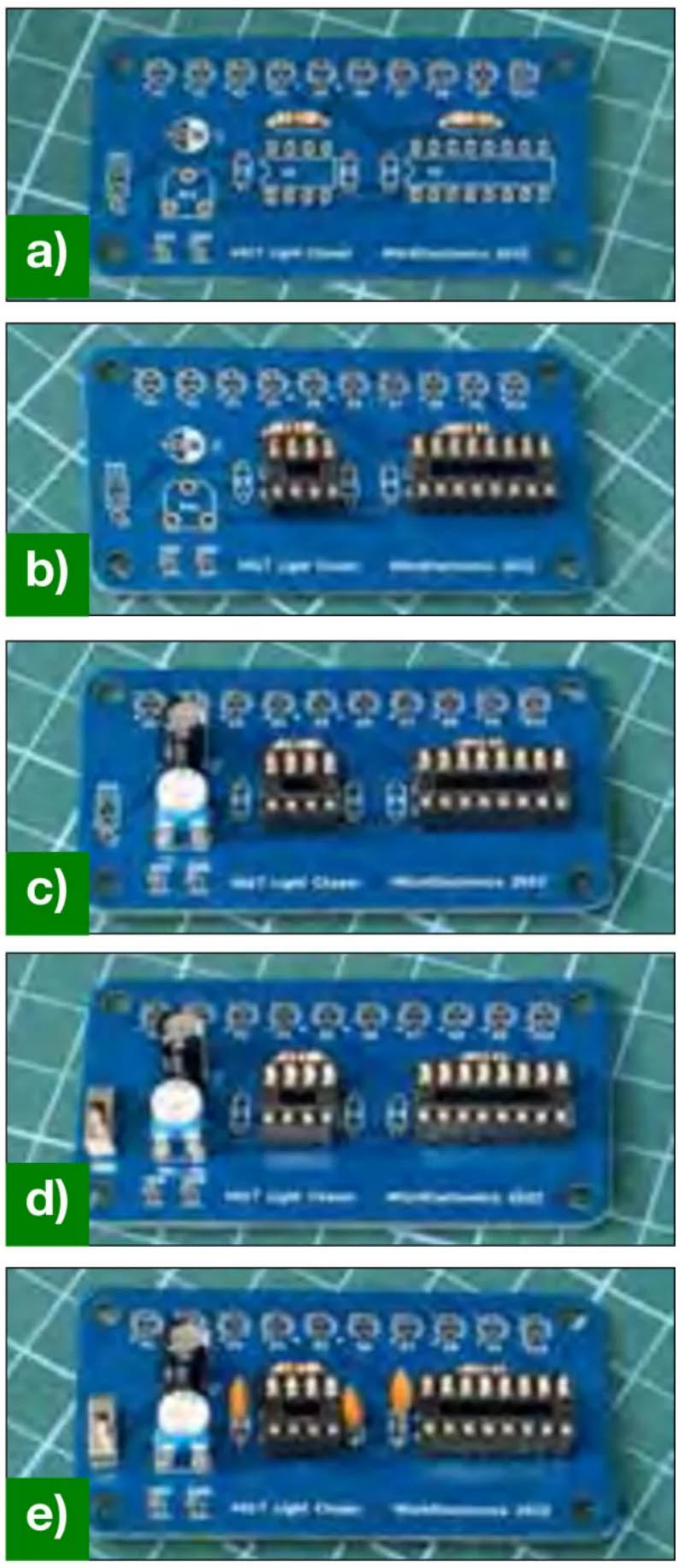


Fig. 21. Construct your *4017 Light Chaser* kit using stages a) to e).

Powering The Projects

One of the great advantages of the kits presented in this article is that they all use PP3 battery connectors, making them easy to power. However, that doesn't mean that they have to be powered by a PP3 battery – they can just as easily be powered using smaller batteries, dedicated PSUs, or even a solar panel.

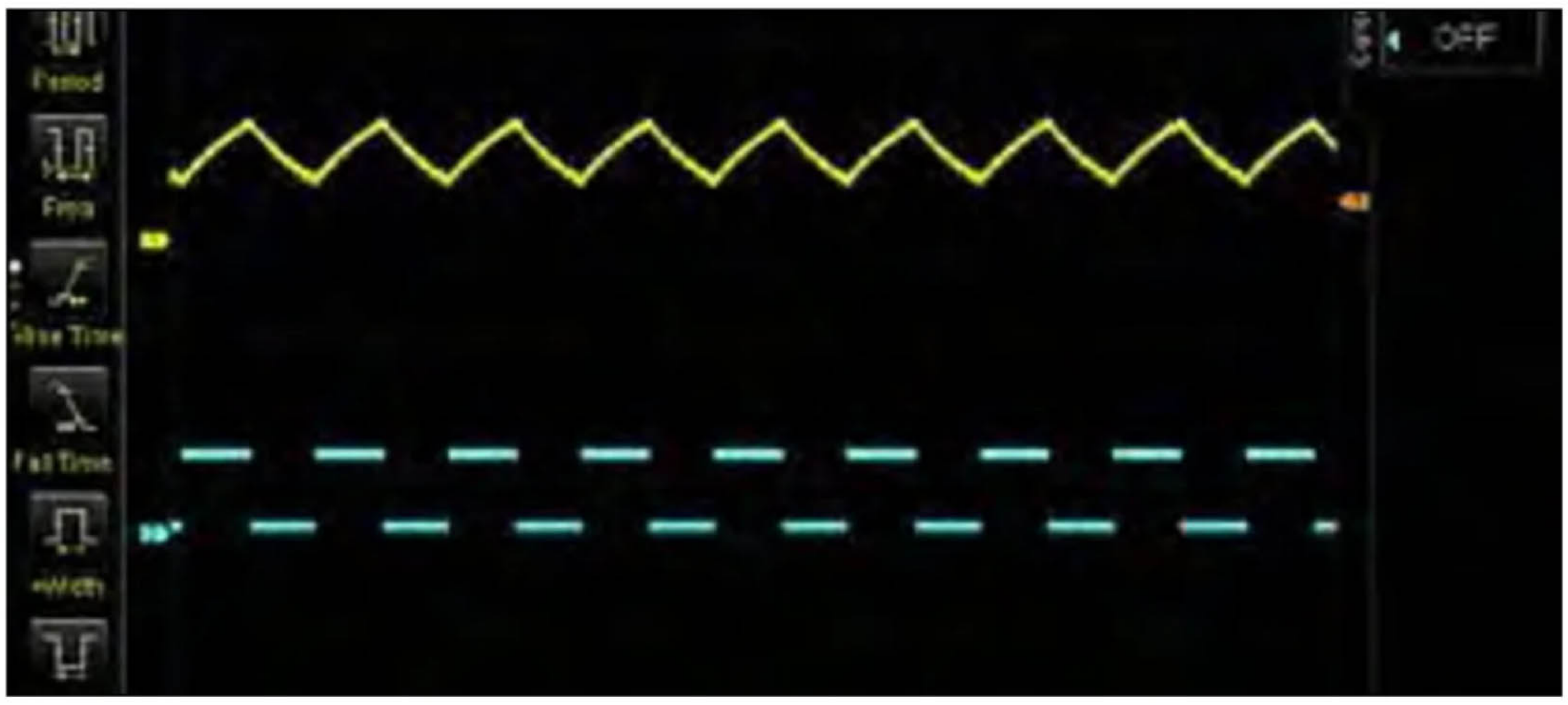


Fig. 23. Oscilloscope showing voltage across the capacitor (top) in an astable circuit (bottom)

While these kits can in theory operate down to 3V, the 555 can be somewhat temperamental at this voltage, so it is recommended that the minimum power supply voltage applied is 4.5V. Furthermore, it should also be noted that the *maximum* voltage is around 16V; going beyond this value could easily damage capacitors and the 555.

Testing the projects

Another handy feature of these kits is that they do not require any specialist equipment to test – good old eyeballs can easily see if LEDs are flashing or not. Most of the kits operate at frequencies low enough that a multimeter can be used to check voltage levels, but in the case of the *Electronic Dice*, an oscilloscope can

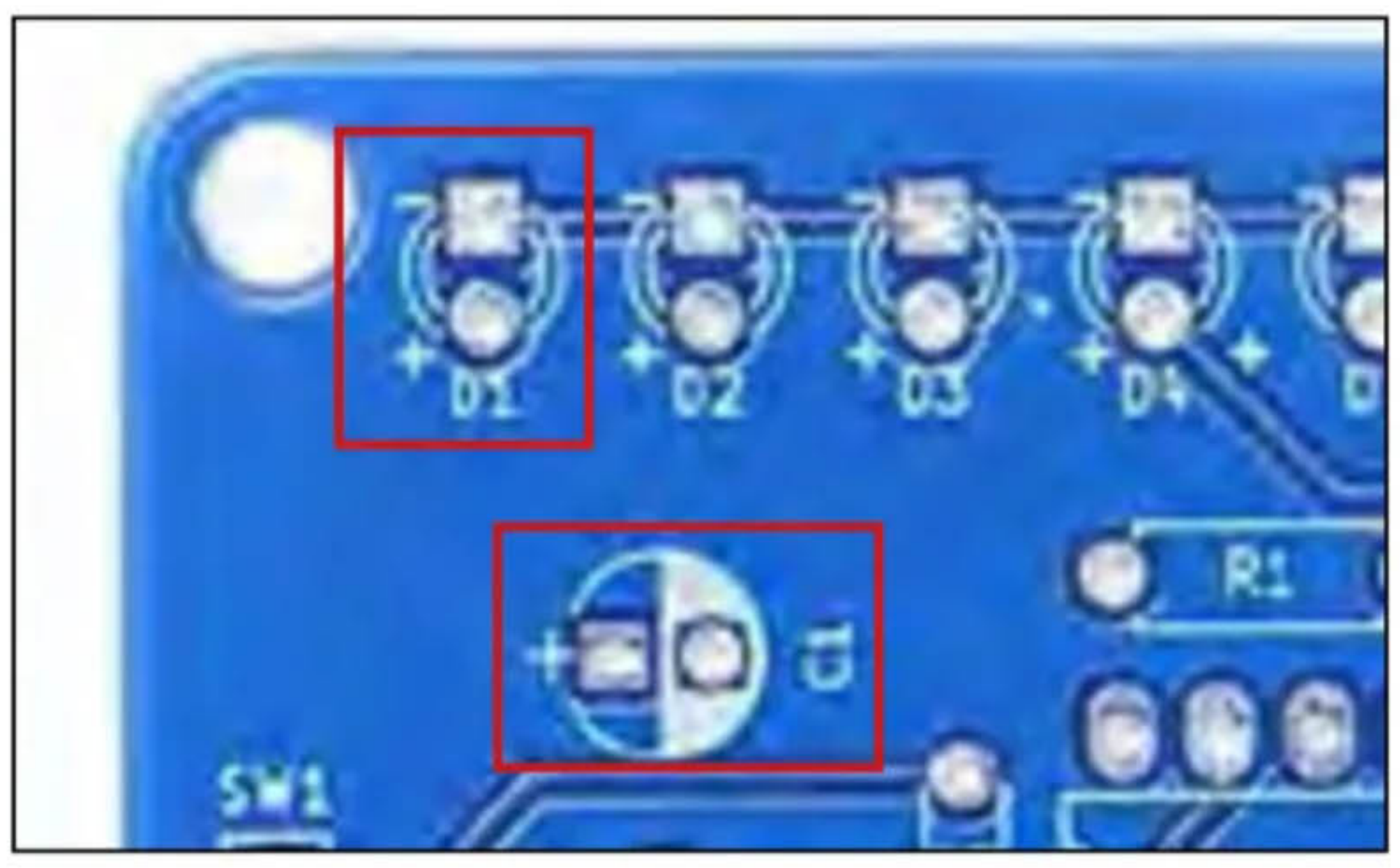


Fig. 22. Check the polarity of the LEDs and capacitors to make sure they are correct.

Part Lists for the kits

4017 Light Chaser Kit
1 x 16 DIP socket
1 x 8 DIP socket
1 x 4017 IC
1 x 555 IC
2 x 1kΩ resistors
3 x 100nF capacitors
1 x 100uF capacitor
1 x 10K potentiometer
1 x small slide switch
10 x red LEDs
1 x PP3 connector
1 x PCB

Electronic Dice Kit
1 x 16 DIP socket
2 x 8 DIP socket
1 x 4017 IC
2 x 555 ICs
2 x 2N3904 NPN trans
3 x 330Ω resistors
1 x 470Ω resistor
1 x 1kΩ resistor
4 x 10kΩ resistor
1 x 680kΩ resistor
6 x 100nF capacitors
1 x 100uF capacitor
1 x tactile switch
7 x red LEDs
6 x 1N4148 diodes
1 x PP3 connector
1 x Dice PCB

Traffic Light Kit
1 x 16 DIP socket
1 x 8 DIP socket
1 x 4017 IC
1 x 555 IC
1 x 10kΩ resistor
1 x 22kΩ resistor
2 x 100nF capacitors
1 x 100uF capacitor
9 x 1N4148 diodes
1 x 4-way pin header
1 x PP3 connector
1 x Controller PCB
3 x 680Ω resistors
1 x red LED
1 x yellow LED
1 x green LED
1 x 4-way pin header
1 x Light PCB

4017 Light Chaser SMD

Electronic Dice

Traffic Light

Scan these QR codes to see additional kit instructions.

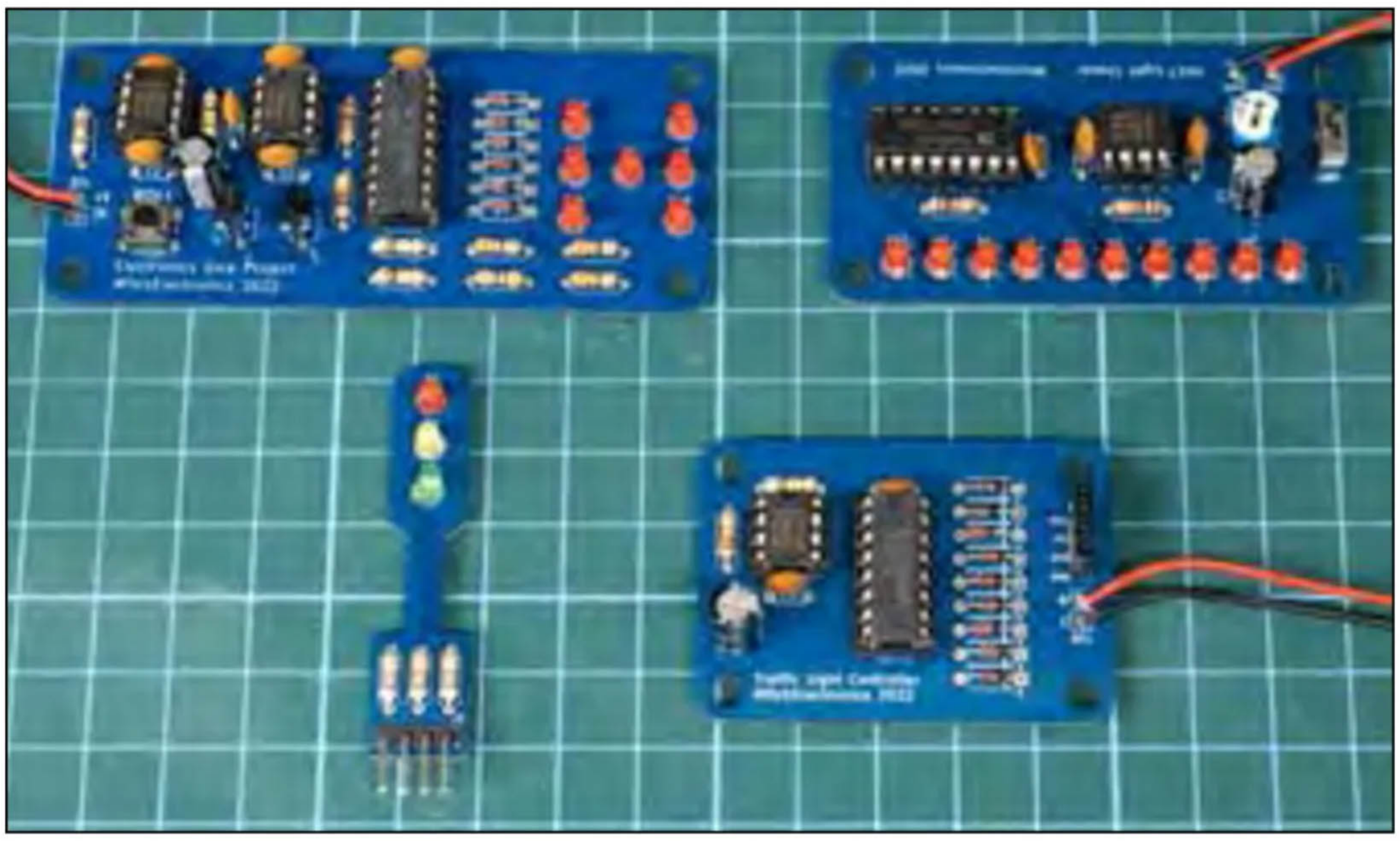


Fig. 23. The completed projects – all three can form the basis of more advanced projects.

be handy in checking the 555 capacitor voltages as well as the output of the 555 timer ICs, as shown in Fig.23.

However, if you are nervous about damaging your kit and have access to a PSU, then you can use the current limiter to prevent the kit from damaging itself. Start by setting the current limiter to its lowest setting, connect the kit, and slowly increase the current level. If the PSU shows current consumption beyond 20mA, then it is possible that something may be wrong (MitchElectronics kits rarely consume more than 50mA).

Troubleshooting

These kits are deliberately simple, so there isn't a lot that can go wrong with them. However, it is more than possible for something to break, whether it is due to incorrectly inserted parts, components being soldered for too long and being damaged by heat, or through static shock that can fry the sensitive electronics inside ICs.

If the kits don't show blinking LEDs when powered, then the first step to do is to check that the LEDs are inserted in the correct orientation, and that they are not damaged. Using the continuity setting on a multimeter, it is possible to probe an LED and power it up slightly to confirm that it is working.

If the LEDs are correctly inserted and working, then it is likely that the ICs are damaged and/or not inserted correctly. Thus, the first step here is to check that the ICs are inserted correctly, taking extra care to see where pin 1 of the IC is (top left pin with the notch facing upwards). If the ICs are inserted correctly, then check the temperature of the IC when it's in operation – an IC that feels very warm or even hot is likely damaged.

Replacing the ICs in this case will resolve 99% of the problems, as the remainder of the components in these kits are passive (except for the transistors in the *Electronic Dice* kit). In the *Traffic Light* kit, the orientation of the external traffic light also matters, so make sure they are have been soldered with the correct orientation. If the *Electronic Dice* repeatedly falls on the same number, then either the 555 monostable is damaged, or the roll button needs to be held for longer.

Taking Projects Further

Besides the obvious uses for the kits mentioned in this article, there are a number of potential project ideas that you can do using them.

The *4017 Light Chaser* which could be integrated into a 'wearable' project – perhaps a *Light Chaser* tie, badge or broach. For those who are familiar with Kraftwerk, such a tie was featured in their music video *The Robots*, and this tie was so brilliant that, when it was introduced in the music video, the cameraman zoomed in on it! See: **https://youtu.be/D_8Pma1vHmw**

The *Traffic Light* is a great kit for those involved with model railways and dioramas, especially for those who reside in the UK. While not quite the correct scale for all models, it can easily be modified to work with pre-existing traffic light designs if the separate traffic light PCB is removed and wires connected to existing LEDs.

Finally, the *Electronic Dice* is a good option for those who want to replace the mechanical dice found in popular board games. It is possible for two to be mounted in an enclosure with the first dice connected to the second via some extra wires so that the second dice continues to roll until the first one has finished (we won't tell you how this could be done, that's a challenge for you to figure out). Our dice only has six faces so it's not ideal for games such as *Dungeons and Dragons*, which use a 20-sided dice.

Remember, if you want to help support our work at MitchElectronics in designing kits for makers and engineers along with educational articles, blogs, and video content, then head over to the MitchElectronics store where you can get all kinds of kits, components, and resources that can help you with your next wonderful project.

In the next article, we will look at a collection of related circuits that measure physical parameters, such as light, sound and temperature. Plus, we will introduce you to the most important class of analogue ICs – the operational amplifier, or 'op amp' for short.

4017 Light Chaser
Traffic Light
Electronic Dice

Fig. 24. This month's collection of kits available from: **https://mitchelectronics.co.uk**

Partnership with PE

MitchElectronics Ltd is an independent UK company. These articles are not 'advertorials', PE does not pay for the articles and MitchElectronics does not pay for their publication.

All the kits/parts described in the series are available from: **https://mitchelectronics.co.uk**

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

Ge semiconductors

Small-signal PNP transistors

NKT214F, OC57, OC59, 2N1377, 2N525	£1.00

Low-noise PNP transistors

GET106	£2.50

Small power PNP transistors

AC153, AC153K, AC188, AC188K	£1.50

Small power NPN transistors

AC176, AC176K, AC187K, AC141K	£2.00

High-voltage PNP transistors

OC77, CV7001	£1.50

TO3 PNP power transistors

OC22, CV7054 (OC23), OC25, OC35, OC36, AD143, AD149, AD161, AD162	£2.00
AD140	£3.50
AD149, AD161/2 matched pair	£5.00

RF PNP transistors

OC41, OC42, 2SA12, 2SA53,AF124, AF178, GET872A	£1.50

NPN transistors

OC139, OC140, ASY73	£2.00

Diodes

CV7049 (OA10), CG92 (OA91)	£0.50

Si semiconductors

Diodes

ZC5800 RF Schottky	£0.20

Low-noise silicon transistors

BFW16A, 2SC3071, 2SC3068, 2SA1016K, 2SC2362K, 2SA970BL	£1.50
2SC2204, 2SD655, BC550C	£0.50
ZTX651	£0.30
ZTX751	£0.50

RF transistors (suitable for Theremin)

BF199	£0.50

Audio power MOSFETs

Exicon 10N20, 10P20	£6.50
Hitachi 2SJ99, 2SK343	£3.50
Hitachi 2SJ56, 2SK176	£8.50

JFETs

BFW11, BFW10, TIS73L, J177, J113, U1994, U1898, 2SJ176, J201	£1.00
J175, J176, J112, J111, 2N3820, 2N5467, BF244, 2N5460, J230	£0.60

Small power output/driver transistors

2SB649A, D669A, 2SA1208, 2SC2910, MJE253G, MJE243G, 2SA1725, 2SC4511	£1.20
BD139,BD140, BD135, BD156, BD435, BD436, MPSA63, BCV46	£0.50

MOSFETs

ZVP2106A	£0.30
Dual-gate 3SK45, BFS28	£1.50

Metal-cased transistors

BC143	£0.35
2N1711	£0.50
BCY71	£0.30
BC109C	£0.60

Amplifiers

LM318 high-speed op amp	£0.35
µA709 metal-cased op amp	£2.00
5534H metal-cased op amp	£3.00
LM384, TDA2030A, TDA2050V	£1.50
TAA435 (Mullard power amp driver)	£1.20

Synthesiser ICs

That/dbx 2180 VCA/VCF	£6.00
CA3080 VCA/VCF (vocoder)	£2.80
CA3280 VCA/VCF	£4.00
LM13600/ LM13700 VCA/VCF	£2.00
CA3086 transistor array	£1.00
PT2399 echo/delay	£1.50

Dual transistors

2N2639, 2N2223, 2N2910 (NPN)	£4.00
E401 (JFET Moog)	£4.00
2SK2145-Y dual JFET	£0.80
2N5564 JFET	£8.00
HN3C51F, HN3A51F	£1.00
DMMT3904/6, HN1A01F, HN1C01F	£0.50

Loudspeakers

PE Mini-Monitor

Volt PE165 6.5-inch woofer (each)	£85
Morel MDT29 tweeter (each)	£25
Kit *pair* of PE165/MDT29 plus Volt crossover parts and PCBs	£299
Monacor DT-28N tweeter (each)	£35
Vifa 19mm BC20SC15-04 tweeter (each)	£15

Volt crossover inductors

1.2mH, 1.5mH, 2mH, 2.7mH, 0.5mH (tapped at 0.3mH) (each)	£5.85

Fully assembled and tested high-quality speaker prototypes – ask for details

LS3/5As and other similar speaker systems (pair)	£200-£350

Fully tested reclaimed speakers

Vifa BC14 5-inch woofer (each)	£10
Vifa TC26 1-inch tweeter (each)	£10

Low-price speakers

Philips 4-inch 4070	£2.00
EMI 10x6-inch, 30Ω Alnico	£7
64mm 64Ω neodymium	£1.20
5x3-inch elliptical 50Ω or 80Ω Alnico	£3.50
1.65x2.75-inch 8Ω	£1.50

Capacitors

Note '10/63' denotes '10µF 63V'.

Polyester

3.3/100, 4.7/250, 4.7/63	£1.00
5.6/63, 8.2/63, 10/63	£2.00
Mullard 'Mustard' C296 0.22/400	£2.00

Polycarbonate

Axial 2.2/63 1%, 4.7/160, 6.8/63	£1.00

Radial

6.8/160V, 10/63	£2.00
Reclaimed 22/63	£2.00

Polystyrene

Philips 1% 4.7nF/160, 6.2nF/500, 12nF/63, 22nF/63, 110nF/63, 24nF, 2nF	£1.00
RIFA 1% 100nF/100, Suflex 90.9nF 0.5%	£2.00
Suflex 2.5% 10nF/63 (rad. or ax.)	£0.50

Radiation resistant

Siemens cellulose acetate MKL 2.2/25	£0.80

Electrolytic – Mullard blue 017 series

10/25, 22/25, 100/10	£0.50
150/40, 470/40, 1000/40	£1.00

Tantalum – axial metal cased

22/50, 47/35, 68/25, 100/20, 120/10, 150/16, 220/10, 330/6	£2.00
22/35, 33/35, 47/20, 68/15, 100/10, 150/6	£1.25
4.7/50, 6.8/35, 10/25, 10/35, 22/15	£1.00

Axial moulded-case tantalum

Kemet axial 6.8/10	£0.30
Kemet radial 33/10	£0.40
STC radial 100/20	£1.50

Tantalum bead

22/50	£1.00
470/3	£2.00
680/6.3	£3.00

Wet tantalum

220/25 axial	£3.20
Castanet button 140/30, 470/3	£3.20
Hughes 540/10	£3.20

Bipolar

Hermetic bipolar tantalum 16/35	£3.20
Elcap axial 10/50	£0.50
Generic radial 100/16, 470/35, 100/ 63, 22/35, 4.7/35, 220/16	£0.50

Philips solid-aluminium (axial) 121/123

47/16	£1.00
330/6.3	£2.00
100/35	£4.00

Philips Pearl 122 series (radial)

10/16	£0.30

Silvered mica (radial)

1nF/500 1%	£1.00

Trimmer capacitors

Vishay plastic-film 4-40pF	£0.80
Vishay plastic-film 5.5-45pF	£1.00
Vishay plastic-film 5-80pF	£1.20
Vishay plastic-film 10-250pF	£2.00
Mica 1-12pF, 2-40pF	£1.00

Audio transformers and inductors

Eagle transformers

LT44, LT722 driver, LT700, LT723 500Ω output	£2.50
LT30 500mW output	£3.50
5:1 interstage	£1.50

Repanco

T/T3 splitter transformer	£4.00
CH2 5mH RFC	£2.00

Balanced output transformer

Vigortronix 600Ω VTX-101-007	£10
Vigortronix 600Ω VTX-101-3001	£10
Vigortronix 600Ω VTX-101-3002	£15
Gardners 150Ω	£10
Reclaimed BBC LL74/MPC nickel core 600Ω	£12

Reclaimed mic input transformer	£15

Inductors

82µH, 4.7mH, 100µH, 270µH, 10µH, 14µH (low Z)	£0.50
7-inch ferrite rod with MW and LW windings	£3.00

Special resistors

Bourns wire-wound trimmer 5kΩ 3059 JM panel-mount	£2.00
Thermistor RA53, R13	£4.00
A13	£2.00
Thermistor CZ1, CZ6	£1.50
Holco H2 2.2MΩ 1W, 1%	£1.00
Welwyn 1GΩ 2W	£1.00
5k Bourns 3321H cermet trimmer	£0.50

Potentiometers

Bourns 81

25kΩ lin cermet	£2.00
25kΩ lin, 5kΩ lin conductive plastic	£3.00

Bourns 91

10k dual-gang lin or log	£10.00

Plessey moulded-track

5kΩ log with switch	£3.00
50kΩ A/log	£3.00
Mil 250kΩ lin dual	£5.00

Alpha

16mm 4.7kΩ A/log	£0.80
220kΩ A/log	£0.80
10kΩ lin centre-detent dual-gang	£1.50

Allen Bradley J series/Honeywell

10kΩ lin 1 million cycles	£5.00
Blore Edwards AB 45 dual 5kΩ A/log with switch	£3.50
Alps RK9 dual-gang 5kΩ RD law	£4.00
Alps 50k log tapped motorised stereo	£5.00
BI P260 500kΩ log conductive plastic 1 million cycles	£2.00
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W	£5.00
Mil Spec hermetic 10Ω	£8.00

Miscellaneous

Theremin Clearance Sale!

Elysian Theremin MIDI box	£300

PCBs

Pocket Theremin (*EPE*, 1996)	£2.00
Elysian Theremin (*EPE*, 1996)	£6
Synth VCF, VCO (*EPE*, 2017)	£3.00
48V PSU (*EPE*, 2019)	£3.00
SMT dual transistor adapter	£0.40

Contact

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The Old Rectory, Arlais Road,
Llandrindod Wells, Powys
LD1 5HE (visit by appointment)

+44 (0)1597 829102

jrothman1962@gmail.com

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Quantity discounts negotiable

Payment

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No VAT payable

Postage

Small Jiffy bag £2.99
Small package £4.99
Big boxes and overseas at cost – ask for a quote

AUDIO OUT

By Jake Rothman

Discrete audio op amp – Part 4

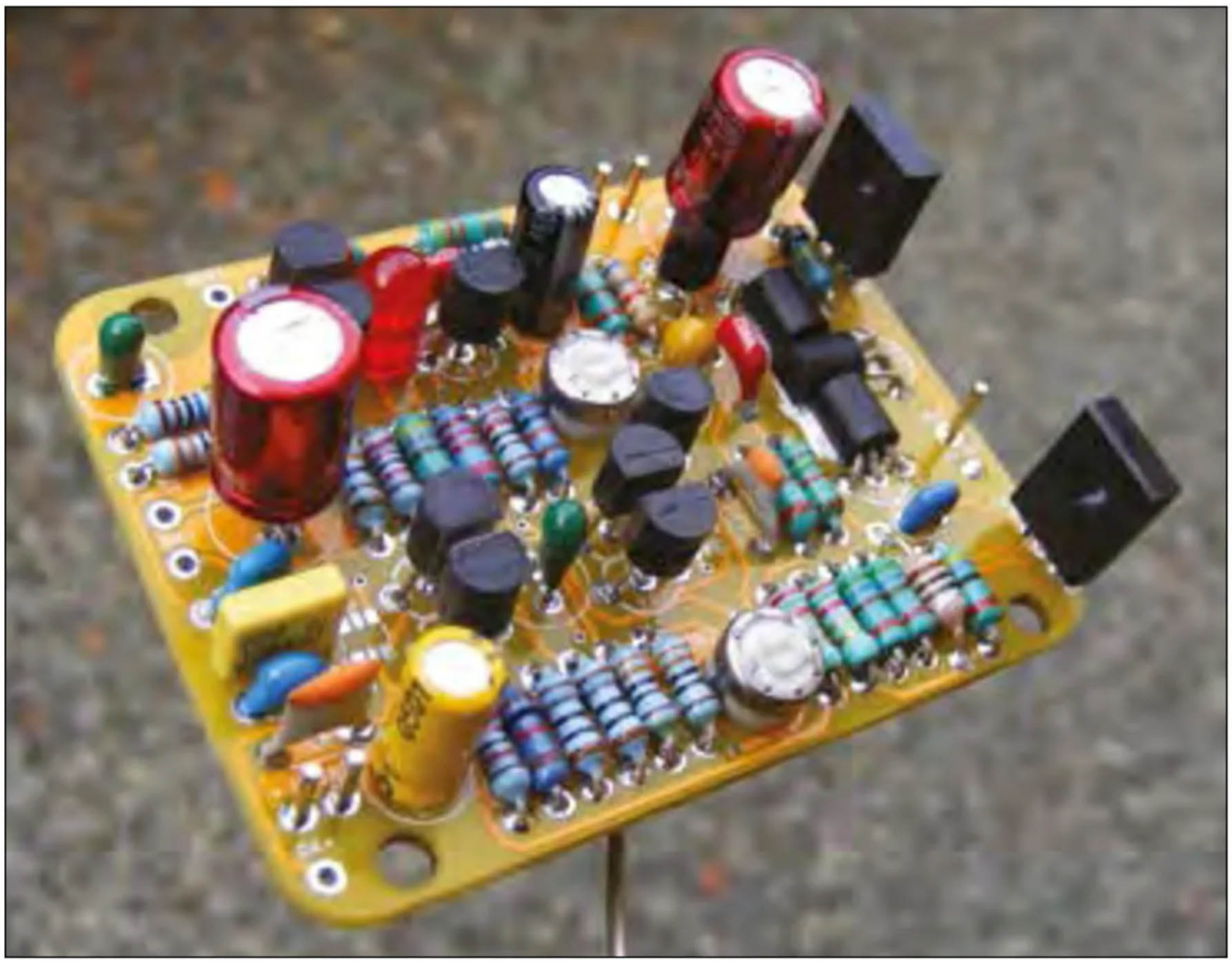


Fig.57. The new *Discrete Op Amp* PCB as supplied by the *PE PCB Service*. It has a new orange colour with some minor modifications. Note the fully insulated ST BD139/40 output devices must have their writing facing outwards from the board.

No circuit design is ever finished – there's always something to change, add or improve – and with that in mind I have a few updates for the *Discrete Audio Op Amp*. First, there is an updated batch of PCBs, which are a new orange colour with locations for the extra R27 resistor, C15 capacitor and input earth pin shown in Fig.35 (*Part 3*). It's pictured in all its glory in Fig.57.

After building 20 boards, it became apparent that some 2SB649AL (TR13, PNP) and 2SD669AL (TR14, NPN) transistors did need C15 for stability, so I recommend always including C15.

The high-power version using the BD139/40 NPN/PNP pair and the above transistors will go up to a frequency limit of 130kHz without problems. I made myself one as a booster amplifier for my signal generator. This was needed for testing the high-voltage buffer amps that we will start describing next month.

Next, I need to make some little additions to the component list in last month's *Part 3*. For the high-power version, R10 is 5.6kΩ to make the I_q preset more likely to be in the middle of its rotation. R27 is 75Ω and C14 is 100µF, 35V to provide higher headroom. This was the biggest capacitor I could find to fit on the PCB and I used a Panasonic ECA1VAM101X (Farnell 876-7254, costs a very reasonable 15p). Note the voltages across the 2.2Ω resistors R11 and R12 are 70mV for optimum I_q of 32mA, the same voltage as the low-power version. For the low-impedance version, R10 is 6.2kΩ. Also, *PE* reader Les Wolstenholme noticed on the Fig.42 circuit diagram that TR10 should be labelled BC327, not BC337.

Mullard muddle

I wrongly castigated the BD139/40 transistors for having higher distortion than other pairs. When I

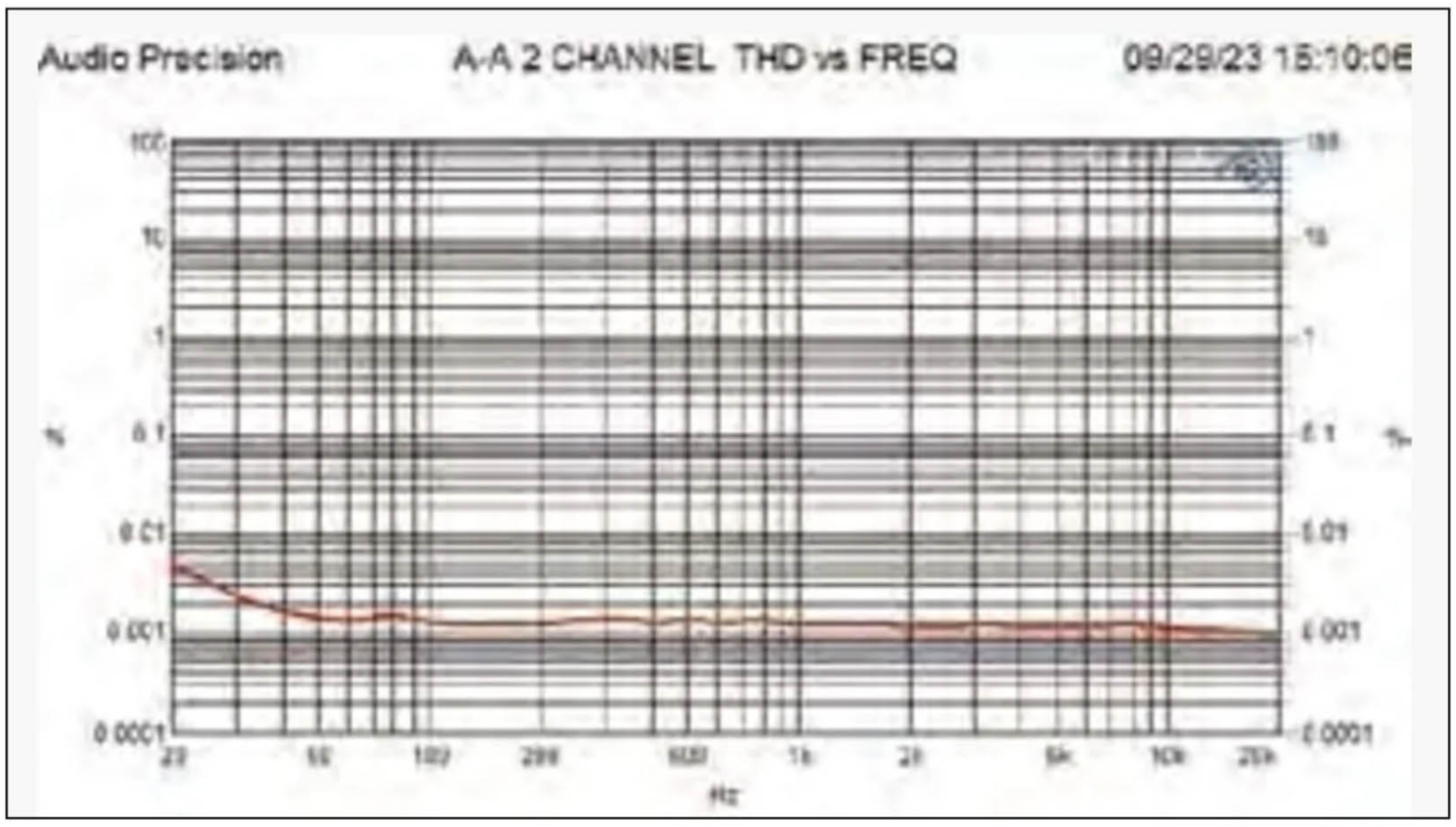


Fig.58. Distortion curve for high-power non-inverting discrete op amp shown in Fig.57 using new ST BD139/40 output transistors and with standard BC546B/556B small-signal devices. For this version, the output is 6V$_{\text{pk-pk}}$, gain of 6, driving 180Ω load and supply of ±25V.

Table 4. Toshiba dual transistor options

Device	Type	Wiring pattern	Optimum source Z	Hfe	Pack code
HN4C06J-BL	NPN	Commoned emitter	700Ω 0.4mA	BL 350-700	DL
HN4A06J	PNP	Commoned emitter	700Ω 0.4mA	200-700	53
HN4A51J	PNP	Commoned base	700Ω 0.4mA	200-700	34
HN4C51J	NPN	Commoned base	2kΩ 0.2mA	200-700	33

used new BD139/40 output transistors made by ST and supplied by Rapid, rather than the old Mullard 1985 ones I used originally, the distortion was as good as the more expensive Japanese transistors: 0.0013%, as shown in Fig.58. I've come across this anomaly a few times before. Semiconductor processing was just not as good 30 years ago as it is now.

Balanced input

Normal differential op amp circuits are rather noisy due to Johnson (resistor) noise. The way round this is to use low-value input resistors, for example, 620Ω. On the down side, this presents a rather low input resistance. A pair of buffers on the non-inverting and inverting inputs can greatly increase this to reduce the loading and hence distortion of the source. (This is an excellent application for the buffers which will be presented next month.)

The distortion of the balanced version was significantly lower than the single-ended design, as shown in Fig.59. This effect happens with most op amps since the common-mode signal (the same voltage excursion across the non-inverting and inverting input terminals) is lower. A photo of the balanced op amp PCB is shown in Fig.60.

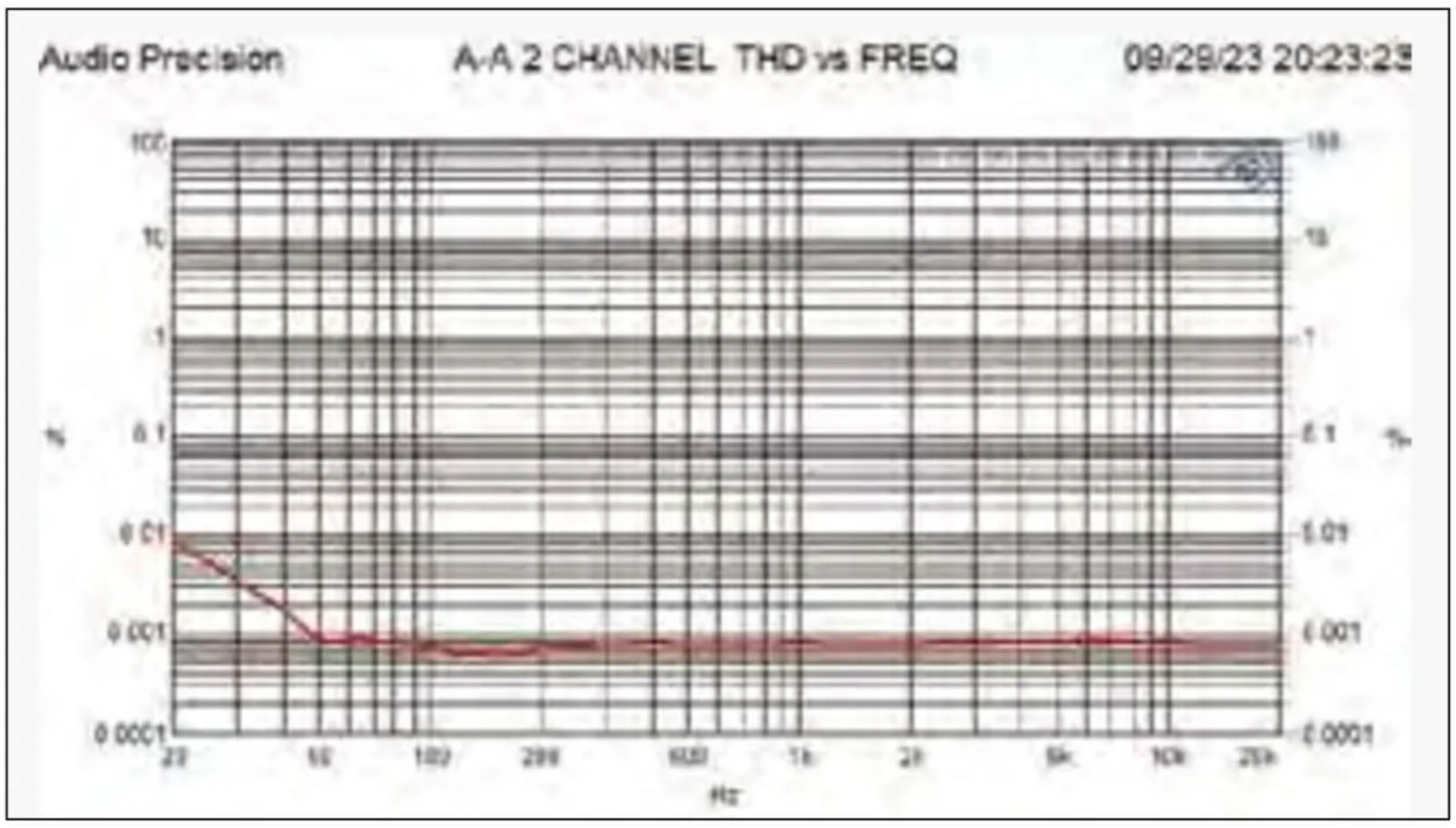


Fig.59. Distortion curve of balanced input discrete op amp using new BD139/40 output transistors. The rise in distortion at low frequencies in this curve (and Fig.58) is caused by the output electrolytic capacitor feeding a low impedance of 180Ω with no polarising voltage. This can be avoided by using a bi-polar type for C10.

Toshiba temptations

I noticed Mouser has some interesting audio dual-transistors manufactured by Toshiba. They can replace the obsolete HN3 types shown in Table 2 (*Part 3*). They have 1dB noise factor curves in their specification, which is an indication of a genuine audio device. However, there's no maximum figure, only 'typical 1dB', which implies there is no individual device testing for noise level. This means the odd unit may be noisy. The maximum ratings are 120V, 100mA, unity gain at 100MHz, 200mW per device, but 300mW pack total. These are ideal for discrete op amps and the inputs for big power amps.

They have the same SOT-26 five-pin pack used by the Toshiba dual-JFET 2SK2145, so they can use the same adaptor board. One version has the emitters joined together for high-gain, long-tailed pairs (where no emitter resistors are used, such as in moving magnet RIAA pre-amps), and the other has the bases joined for current mirrors. They are available in both PNP and NPN varieties. When I measured them, the typical H_{fe} was 500 and the

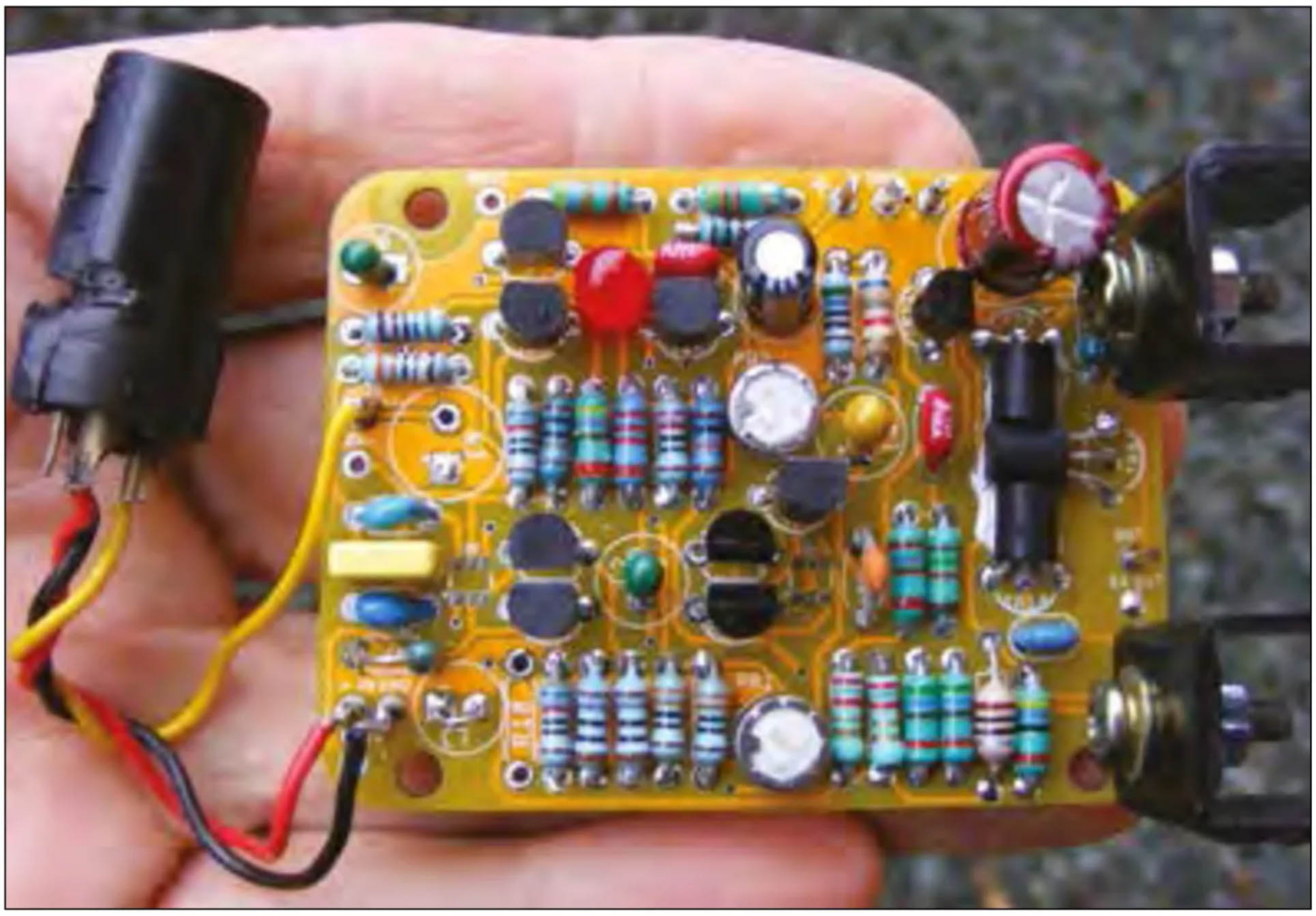
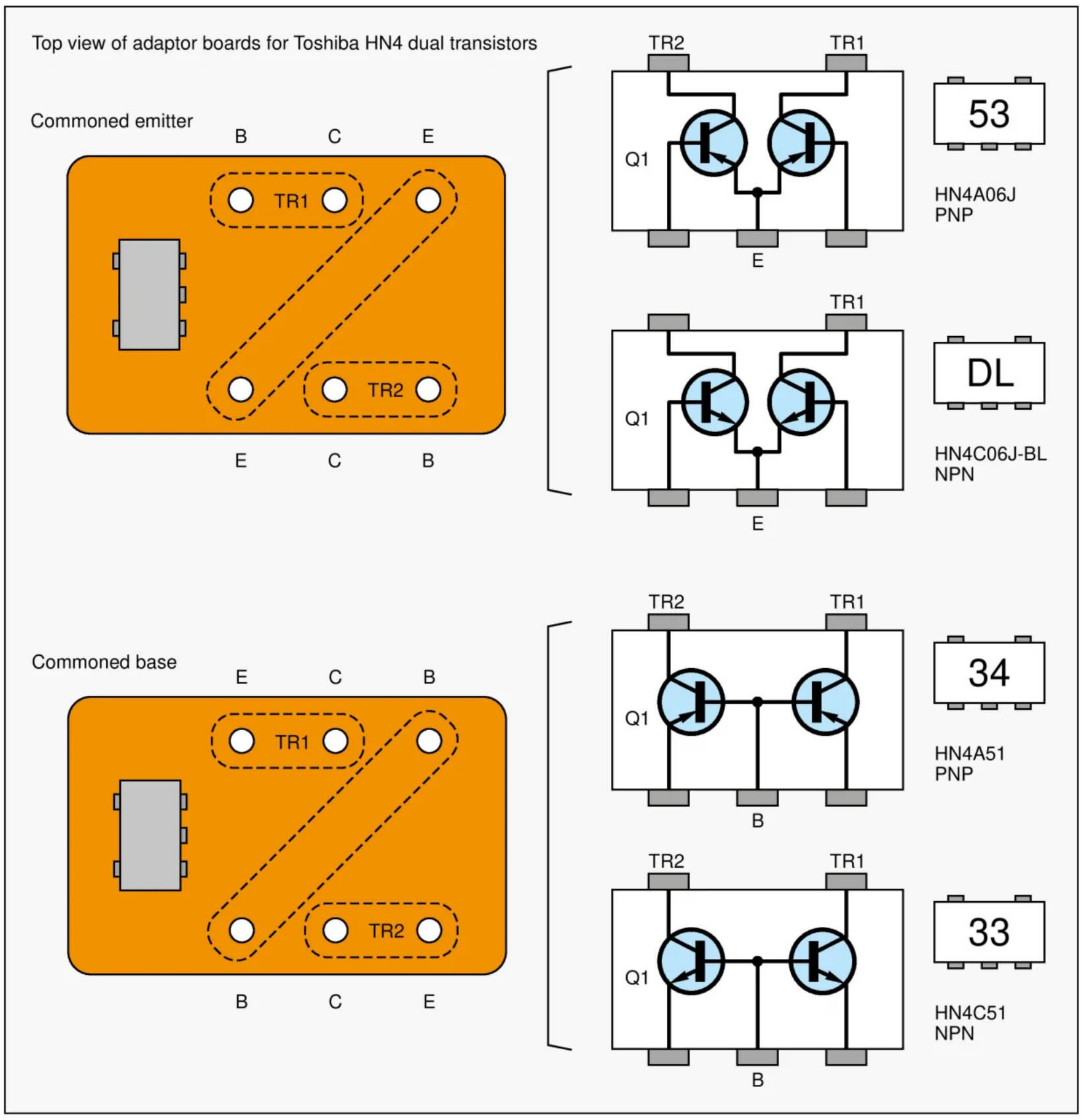


Fig.60. Balanced input version of discrete op amp PCB. This will help in conjunction with the diagram (Fig.37) in *Part 3*. Using 620Ω input resistors (R19 and 20) and 2kΩ for R21 and Rgnd (in C8 position) in the diagram in Fig.37 (*Part 3*) allows a useful balanced amplifier with a gain of 4x to be built. The input XLR connector wiring is: red for the non-inverting input, yellow for inverting input and black for 0V. Note: C7 is linked and C8 has a 2kΩ resistor vertically mounted (above pins for red/black wires lower left)


Top view of adaptor boards for Toshiba HN4 dual transistors
Commoned emitter
B C E
TR1
TR2
E C B
Commoned base
E C B
TR1
TR2
B C E
TR2 TR1
Q1
E
53
HN4A06J
PNP
TR1
Q1
E
DL
HN4C06J-BL
NPN
TR2 TR1
Q1
B
34
HN4A51
PNP
TR2 TR1
Q1
B
33
HN4C51
NPN

V_{be} was 0.74V with excellent matching. I've not yet tested them for noise. I did crack one open and was surprised to see it consisted of two separate dies. I suspect they were adjacent dies on the same silicon wafer, given the excellent matching. The pin-out details are shown in Fig.61 and summarised in Table 4.

Discrete op amp kit

A kit of parts is available from the *PE PCB Service*. This comprises the main PCB, the SMT J-FET adaptor board, all capacitors, a 2SK2145 SMT J-FET, two Toshiba SMT dual transistors, two miniature 5kΩ presets, the inductor and heatsinks.

That – for now – concludes the *Discrete Audio Op Amp* design. Next month, I will follow up with a new series on a related circuit for an *Audio Buffer* – discrete, of course!

Fig.61. Pack outlines for commoned-connection Toshiba dual-transistors. Note that the collectors are the middle pins (C) on the adaptor boards, so a pair of crossed wires will be needed to mount them on the discrete op amp PCB.

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Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
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Steam Train Whistle / Diesel Horn Sound Generator	09106181	£8.50
Universal Passive Crossover (one off)	UPC0320	£12.50
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DSP Active Crossover (Front panel)	01106195	
DSP Active Crossover (LCD)	01106196	

PROJECT	CODE	PRICE
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Isolated Serial Link	24107181	£8.50
DECEMBER 2019		
Extremely Sensitive Magnetometer	04101011	£16.75
Four-channel High-current DC Fan and Pump Controller	05108181	£8.75
Useless Box	08111181	£11.50
NOVEMBER 2019		
Tinnitus & Insomnia Killer (Jaycar case – see text)	01110181	£9.95
Tinnitus & Insomnia Killer (Altronics case – see text)	01110182	£9.95
OCTOBER 2019		
Programmable GPS-synced Frequency Reference	04107181	£11.50
Digital Command Control Programmer for Decoders	09107181	£9.95
Opto-isolated Mains Relay (main board)	10107181	£11.50
Opto-isolated Mains Relay (2 × terminal extension board)	10107182	
AUGUST 2019		
Brainwave Monitor	25108181	£12.90
Super Digital Sound Effects Module	01107181	£6.95
Watchdog Alarm	03107181	£8.00
PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
PE Theremin component pack (see p.56, August 2019)	PETY0819	£15.00
JULY 2019		
Full-wave 10A Universal Motor Speed Controller	10102181	£12.90
Recurring Event Reminder	19107181	£8.00
Temperature Switch Mk2	05105181	£10.45
JUNE 2019		
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APRIL 2019		
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MARCH 2019		
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+Processing Board	04101182	£8.60
FEBRUARY 2019		
1.5kW Induction Motor Speed Controller	10105122	£24.95
NOVEMBER 2018		
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OCTOBER 2018		
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	10108162	
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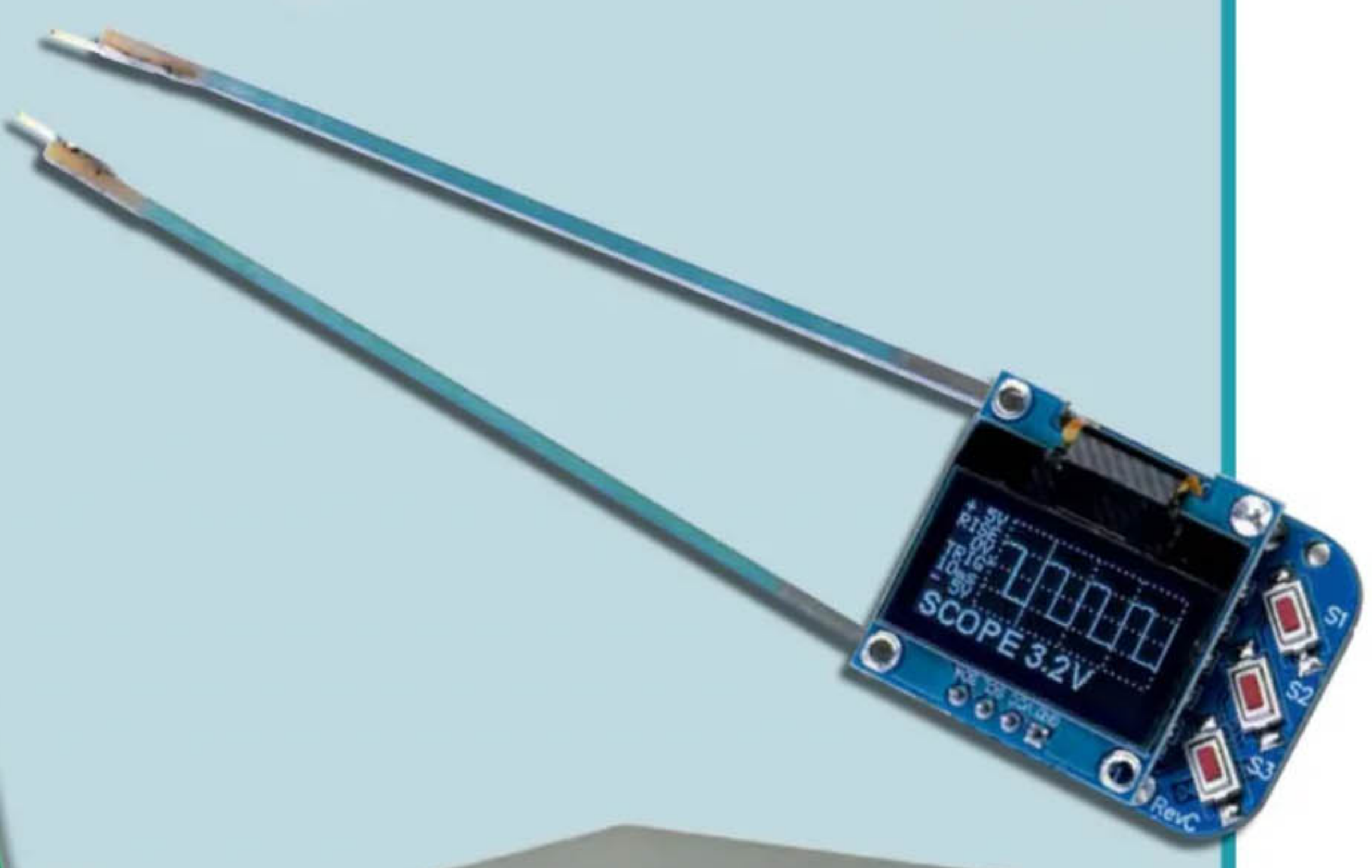
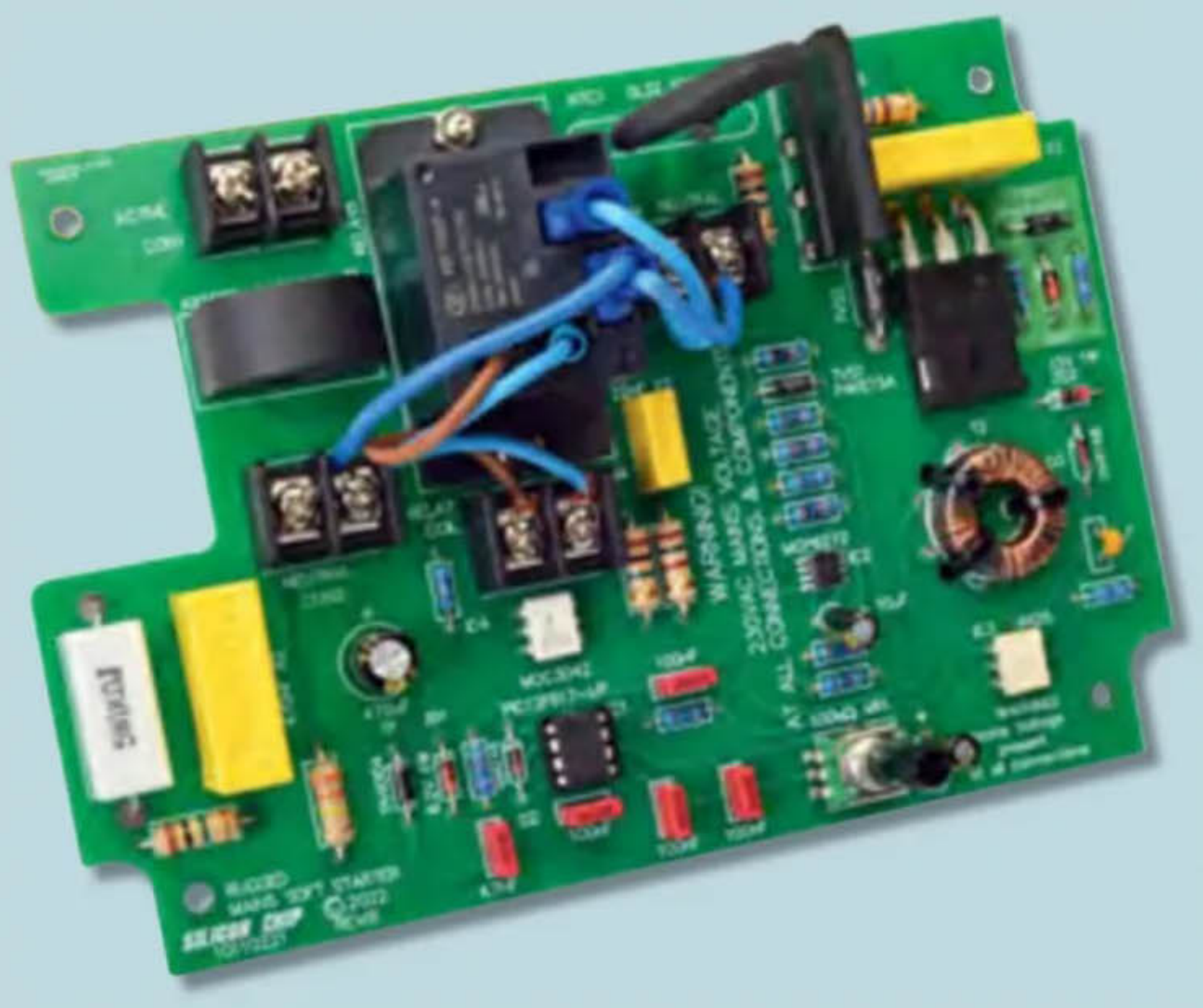
Next Month – in the February issue



Advanced SMD Test Tweezers – Part 1

The SMD Test Tweezers and their successor, the Improved SMD Test Tweezers, are both simple but useful tools. We have developed an enhanced version with many more features and other improvements, such as a larger screen and an easier-to-use interface.



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Active Subwoofer –Part 2

In this second and final article in the series, we'll finish off the Active Subwoofer by building and installing its internal 180W amplifier, finishing the wiring, installing the driver and adding some feet.

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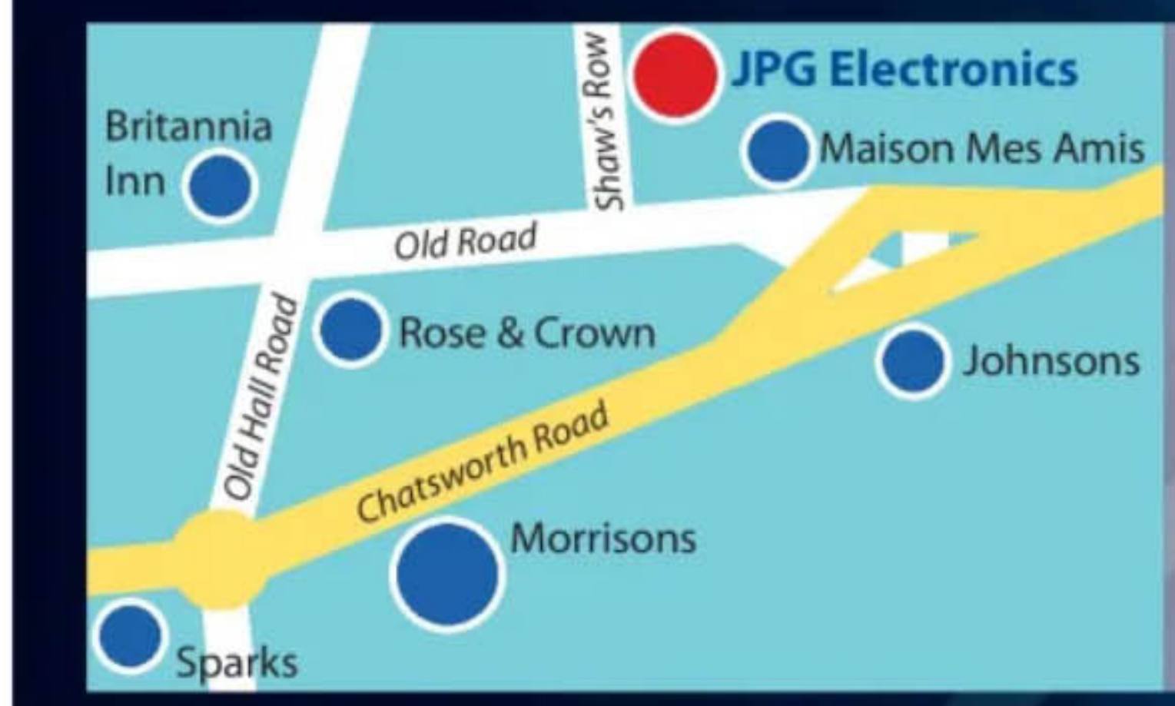

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